AD-A042 272 INSTITUTE FOR DEFENSE ANALYSES ARLINGTON VA SCIENCE A--ETC F/G 21/4
DOD ENERGY R AND D. PART II. MILITARY FUEL OPTIONS. PERFORMANCE--ETC(U)
MAR 77 F R RIDDELL, R C OLIVER DAHC15-73-C-0200

UNCLASSIFIED P-1116-PT-2 NL

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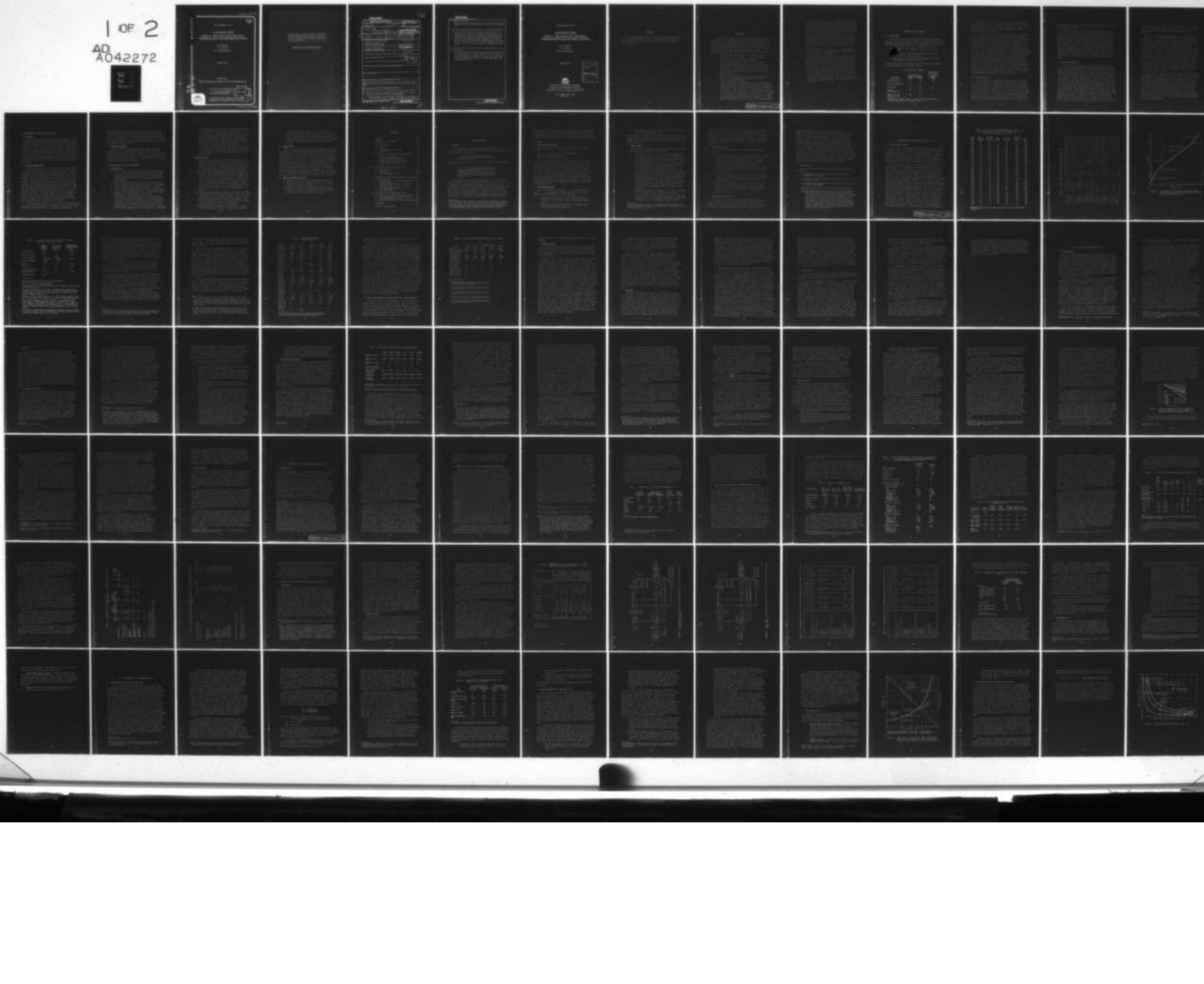

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IDA PAPER P-1116

DoD ENERGY R&D
PART II: MILITARY FUEL OPTIONS-- PERFORMANCE AND R&D IMPLICATIONS

F. R. Riddell
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March 1977

Prepared for

Office of the Director of Defense Research & Engineering

IDA

INSTITUTE FOR DEFENSE ANALYSES
√SCIENCE AND TECHNOLOGY DIVISION

IDA Log No. HQ 76-18966

The work reported in this document was conducted under contract DAHC15 73 C 0200 for the Department of Defense. The publication of this IDA Paper does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official position of that agency.

(12)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER PAPER P-1116	2. GOVT ACCESSION NO. and	3. RECIPIENT'S CATALOG NUMBER (9)
4. TITLE (and Subtitle) (6) DoD Energy R&D. Part II. Military Fuel Options. Performance and R&D Implications.		5. TYPE OF REPORT & PERIOD COVERED Final rept. April 1975-Sept 1976
		6. PERFORMING ORG. REPORT NUMBER (14) P-1116-Pt-2
7. AUTHOR(s) (10) F.R. Riddell, R.C. Oliver, R.E. Reichenbach		8. CONTRACT OR GRANT NUMBER(s) (15) DAHC15-73-C-0200
9. PERFORMING ORGANIZATION NAME AND ADDRESS INSTITUTE FOR DEFENSE ANALYSES 400 Army-Navy Drive Arlington, Virginia 22202		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task T-116
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency 1400 Wilson Boulevard Arlington, Virginia 22209		12. REPORT DATE (11) March 1977
		13. NUMBER OF PAGES 92
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) DD(Research & Advanced Technology), ODDR&E		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited. (12) 103p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N/A

18. SUPPLEMENTARY NOTES

N/A

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Defense Energy R&D, Military Fuel Options, Military Multifuel Engine Benefits, Multifuel Engine R&D, Military Fuels R&D, Alternative Military Fuels

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The questions addressed and the conclusions reached in this study are:

1. What range of multifuel capability may be desirable in military engines to relieve possible fuel supply problems?
   - The conclusion is that it would be advantageous for military aircraft to be able to use all types of jet fuels and for ground

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20. ABSTRACT (Continued)

vehicles and ships to be able to use all types of diesel fuels as safeguards against short-term shortages of military specification fuels.

(2) What liquid hydrocarbon fuel options may be considered without incurring major performance degradation or severe maintenance problems?

- The conclusion is that with appropriate modifications to fuel supply and starting systems, the range of fuels defined in (1) could be used. However, R&D is needed to determine exactly what modifications are required and how fuels may be field-tested. More R&D is also needed to assemble handbooks of information on operating envelope and maintenance changes that may result from use of off-specification fuels. Current information is far from complete. Fuels from syncrudes should be included in this R&D work.

(3) In the long-term, what alternatives to liquid hydrocarbon fuels can be considered?

- In the long-term (beyond 2000) the only possibilities appear to be (a) more extensive use of nuclear power in Navy ships and (b) use of liquid hydrogen in long-range aircraft. For all land and air tactical combat vehicles, however, any change from liquid hydrocarbon fuels would involve major performance changes which are probably unacceptable.

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Contract DAHC15 73 C 0200

Task T-116

FOREWORD

Most of the data on which this paper is based was collected in the spring and summer of 1975. The conclusions reached have been reviewed more recently (January 1977) and are believed to be still valid.

ABSTRACT

In Part I (IDA Paper P-1116, June 1975) of this study, "An Evaluation of Technology Base Energy R&D Objectives," it was concluded that a reasonable goal for Technology Base R&D would be to extend military fuel options beyond the particular military specification petroleum fuels now used. Part II, which is reported here, examines this broad goal in more detail. The questions addressed and the conclusions reached are as follows:

1. What military fuel options (i.e., range of multifuel capability) may be desirable to relieve possible liquid hydrocarbon fuel supply problems?

- The general conclusion is that it would be advantageous for military aircraft to be able to use all types of jet fuels and for ground vehicles and ships to be able to use all types of diesel fuels as safeguards against short-term shortages of military specification fuels.

2. What liquid hydrocarbon fuel options may be considered without incurring major performance degradation or severe maintenance problems?

- Use of the range of fuels defined in 1 above should not cause unacceptable performance degradation or maintenance problems provided the engines have appropriate modifications made to their fuel control and starting systems and provided that any associated limits on operating envelopes are established. Technology Base R&D efforts are needed to determine what modifications are required to accommodate off-specification fuels and to improve understanding

of life, operating envelope, or performance limitations that may result from use of off-specification fuels or fuel blends. This R&D program must include fuels derived from syncrudes since such fuels can be expected to appear within the lifetime of military equipment now coming into use. It is recommended that handbooks on off-specification fuel usage be developed and updated as more information is gained in the R&D program. Such action would provide some insurance against military operations being curtailed by liquid hydrocarbon fuel supplies being squeezed in conceivable emergency situations.

3. In the long-term, what alternatives to liquid hydrocarbon fuels can be considered without degrading vehicle performance requirements?

- In the long-term (beyond 2000), the only possibilities of reducing military dependence on liquid hydrocarbon fuels appear to be by greater use of nuclear propulsion and eventual use of liquid hydrogen in some applications. For the foreseeable future, however, such possibilities are limited to Navy ships for nuclear propulsion and to very-long-range aircraft missions for liquid hydrogen, if performance loss is to be avoided. For all land and air tactical combat vehicles, any change from liquid hydrocarbon fuels would involve major performance changes which appear at present to be unacceptable.

SUMMARY AND CONCLUSIONS

A. BACKGROUND

In Section II it is shown that military fuel demands are concentrating in the middle distillates, trending away from both gasolines and residual fuels. This change has been under way for over twenty years. The major influences have been:

- The switch to gas turbines on nearly all military aircraft.
- The decision to have military ground vehicles over about 150 hp use diesel engines.
- The decision to switch military steam-powered ships from residual fuels to distillates.

This trend and the relationship of military demand to domestic demand are shown in the following table.

MILITARY FUEL DEMANDS

Fuel Type	Percentage of Military Demand 1950	Percentage of Military Demand 1975	Approximate Percentage of Domestic Demand 1975
Motor Gasoline	3	4	0.5
Aviation Gasoline	18	2	*
Jet Fuels	14	60	33
Diesels (Distillates)	17	19	3
Heavy Oils and Residual Fuels	48	15	2

*Depends on octane rating. The military are shifting to lower octane fuels to broaden supply.

A further factor enters in that a standarization of military jet fuels to aviation kerosenes has been sought, replacing JP-4 (primarily naphtha) with JP-8, a kerosene. If this change takes place, almost all military fuels will be high boiling distillates (>300° F).

In general, the domestic supplies suggested in the table are not fully available to the military since the possible military need to operate under extreme environmental conditions had led to fuel specifications more severe than those for civilian fuels. Present specifications were originally established in an era of ample supply, and merit continuing re-examination. For aviation kerosenes and diesel fuels, freezing point and flash point specifications are particularly significant to supply. For any given vehicle, use of off-specification fuels (high freezing point, e.g.) could limit its operating envelope; the limitations are poorly known and need to be established. Within the limited operating envelope, however, performance should be unaffected by relaxation in at least certain of the critical specifications. These points are further considered in the following discussion, which addresses the question of the supply benefits and the performance and cost penalties associated with broadening military fuels specifications, i.e., with providing multifuel capability in military vehicles.

B. MULTIFUEL BENEFITS

The major benefit of multifuel operation is to increase the effective supply of fuel when spec fuels become in tight supply. The question is how great a distillate range coverage is needed. Civilian production of diesel fuels is roughly 30 times military consumption; hence, for ground vehicles and ships an ability to use all types of diesel fuels would provide a very large supply potential. Wartime military demand may be three times as large but even so, domestic supplies (and stored reserves) would seem to provide a sufficient supply reserve. It

is difficult to imagine a scenario where greater multifuel capability would be needed.

With regard to jet fuels, the supply situation is much different. If sustained military wartime demand were doubled or crude oil supplies were halved, then domestic supplies would be heavily squeezed. From the supply viewpoint, therefore, there would be advantages to providing military aircraft with multifuel capability on as wide a range of jet fuels as possible, taking into account, that not all military aircraft have the same fuels requirement. Some relief could undoubtedly be obtained by changing the mix of refinery outputs; however, establishing the extent to which this may be possible under various circumstances is a question which is important to, but has not been part of, this study, as noted in the conclusions (page xiii).

C. MULTIFUEL PENALTIES

As indicated in discussing fuel specifications, in many cases a multifuel capability may be accomplished with relatively minor engine modifications, such as adjusting fuel control systems for different fuel viscosity. Navy carrier aircraft have been required to operate on JP-5 (a kerosene) while on ship and on JP-4 while on land. Switchover involves minor fuel system adjustments to maintain power levels. JP-4 is in a sense at one end of the current range of jet fuels and JP-5 at the other, so one would expect that these aircraft could accommodate all types of jet fuel (military and civilian) if the proper adjustments were determined. Most Air Force aircraft do not have this capability but some could apparently acquire it with engine accessory changes while others may need more extensive modifications. More information needs to be developed to settle these questions. Diesel engines for ground vehicles can operate on a range of diesel fuels, and possibly on some heating oils, but fuel and/or

air heaters may be required. Navy steam systems can use a wide range of distillates without major problems, though such secondary problems as seal failures have occurred when fuels are changed.

Major engine redesign problems appear if it is desired to extend multifuel capability beyond the normal distillate range. For example, in attempting to make an engine run on either gasoline or diesel fuel, the basic combustion process is affected and this necessitates a complete new engine development. Obviously, even if a radically new engine were successful, many years would be required before the inventory of existing equipments would be affected. Viewing this problem in conjunction with the supply situation, it appears that most of the benefits of diesel engine multifuel operation could be obtained by providing the modifications needed to use all diesel fuels, such as the type of adjustments carrier aircraft now have, together possibly with fuel or intake air heaters. Trying to extend multifuel capability to greater distillate ranges that involve major engine redesign gets into considerably greater cost and the benefit increase appears to be small.

There does not appear to be any technical conflict between the military desire for standardized fuels for normal operations and a multifuel capability for emergency situations although cost (supply/demand) questions arise. Independent of this consideration, it is necessary to have complete fuel/performance information (perhaps as handbooks) which would detail the results and operating limitations imposed by non-specification fuels. At present this information appears in various tech orders and operating instructions but not in a coherent way. There are also many gaps since testing engines on non-specification fuels is expensive and has not been a priority requirement in previous R&D programs.

D. ADDITIONAL FUEL SUPPLY POSSIBILITIES

1. Syncrudes

Coal and oil shale appear to be the only domestic sources of syncrudes large enough to impact the supply program. Syncrudes, and jet and diesel fuels, can be made from either raw material; in the near-term, however, the state of technology, production economics, and the reserves situation make oil shale the more attractive source for military fuels. Nevertheless, both sources should be considered in technology base efforts to characterize possible future fuels. The Navy has under way a continuing program to establish (in conjunction with ERDA) a limited shale oil facility to provide products for test and evaluation.

2. Liquid Hydrogen (LH_2)

It is unlikely that LH_2 will be used as a military fuel in the near future because of its handling and storage problems, its relatively high cost, and low supply situations. Overall industrial use of hydrogen is steadily increasing and, as conventional fuels increase in costs, a lower ratio in total cost of LH_2 to petroleum fuels might be expected. There are long distance flight missions of increasing importance for which LH_2 fuel could actually provide a factor of two greater range and endurance than can be attained with petroleum fuels. Thus it is conceivable that LH_2 may eventually be a fuel for some military aircraft. On the other hand, military high-speed and/or low-altitude aircraft or missiles are volume-sensitive and generally could not use LH_2 without severe performance losses. Probably no more than half of the military aircraft fuel requirements are accessible to use of LH_2.

It has been shown that LH_2 can be used in jet engines without major redesign problems. Production, storage, and handling problems are becoming routine as industrial usage grows. The

space program developed much technical knowhow in this area, including the originally troubling problem of hydrogen embrittlement. None of these areas are severe impediments to the use of LH_2 as a military fuel. Its eventual use will depend on the extent of the demand for very long-range aircraft and the cost and availability of LH_2 as a fuel.

3. Nuclear Propulsion

Nuclear propulsion will probably be confined to ocean-going ships for the foreseeable future, if only because of safety problems in other types of vehicles. In ship applications there is a potentially significant cost benefit in reducing the specific weight of nuclear systems so that they may be used more effectively on escort-size vessels.

E. CONCLUSIONS AND R&D IMPLICATIONS

1. R&D on Fuels

- For conventional fuels, research on additives, blends, etc., should be concentrated on making the full range of middle distillate fuels usable in military diesel engines and the range of all jet fuels usable in military aircraft.
- Fuels research outside these distillate ranges is of minor importance, e.g., the Army program on classifying various crudes for emergency use may be of marginal value. Burning crudes in diesel engines presents major problems and other solutions, e.g., portable refineries appear to be available (see Section III-C).
- Investigations of syncrude products should continue, recognizing severe uncertainties in the future supply situations. Syncrude supplies could not be rapidly increased should an embargo or other step change in the supply/demand ratio occur, but could provide a dedicated source less vulnerable to public pressure in a protracted

"squeeze" situation. Fuels from oil shale would appear to be preferable (lower cost) for military needs to fuels from coal. Technology Base R&D on these products should include refining, combustion, product stability, and economic studies, as DOD must be a knowledgeable buyer. The testing of products should not be carried out with poor quality, severely off-specification fuels to avoid the obtaining of misleading results.

- The extent to which refineries can adjust product mix on a short-term basis, and the implications with regard to the need for multifuel operation, should be given further study.

2. <u>R&D on Engines</u>

- R&D that would make jet engines automatically or semi-automatically tolerant to all types of jet fuels is needed. Primary requirements are for fuel systems that adjust to viscosity, starting capabilities that adjust to volatility changes, and for fuel heater systems.
- In view of the potential emergency supply problem with jet fuels, the possibilities of making jet engines tolerant to a wider range of fuels (naphthas through diesels) look attractive. R&D programs on combustor life and special starting systems or techniques are appropriate. The extent to which such programs are pushed should, however, follow from a better evaluation of the degree to which refineries can adjust output mixes on demand.
- To extend fuel tolerance, diesels, like jets, also need automatic or semi-automatic adjustment of fuel injection controls to viscosity changes, as well possibly as fuel and air heaters and special starting techniques. The variable compression ratio piston developed for an Army tank engine may contribute to this program.
- Multifuel gasoline engines are much harder to produce than either diesels or jets. The Army has pursued a

stratified charge engine for the jeep which is now reaching completion. R&D programs to extend this concept to higher horsepower seem less productive than making multifuel diesels (possibly with variable compression ratios) provided the power requirement is over 150 hp.

3. General R&D

There is a great need for overall documentation of the operational and maintenance problems associated with use of fuels which may not meet full military specifications (in terms of freezing point, vapor pressure, etc.) but which are otherwise satisfactory in a quality sense, as for example in the substitution of Jet A for JP-8 or JP-5. Current information exists in diverse documents and testing has been inadequate due to the costs involved. An R&D program involving engine, fuel and vehicle specialists to coordinate the overall problems and define proper field actions would be appropriate. This would involve considerable judgment since it seems clear that complete full-scale testing of all conditions would be too expensive.

4. R&D on Conceptual Vehicles

- There is a need for continued investigation of the potential benefits of applications of LH_2 to long-range military aircraft missions.
- There is a need for continued investigation of the potential benefits of lightweight nuclear propulsion systems for small ocean-going Navy ships.

CONTENTS

I. STUDY APPROACH

A. PURPOSE

This report is in response to the second part of a Task Order entitled "R&D On Energy Management" (see Appendix A), the central purpose of which is:

> To review DOD energy uses and develop guidelines for Technology Base* R&D on energy management.

The purpose of this part of the study is stated in the Task Order to be:

> . . . to survey the possible impact on the DOD energy management problem of R&D programs related to fuel options. This will include multifuel capability in liquid hydrocarbons and possible future alternate fuels, specifically hydrogen and nuclear sources.

A previous report (IDA Paper P-1116, June 1975) directed at the first part of the task and entitled "DOD Energy R&D, Part I--An Evaluation of Technology Base Energy R&D Objectives" concluded that primary goals of DOD Technology Base Energy R&D should be, first, to maximize petroleum fuel options for combat forces and, second, to reduce dependence on petroleum fuels. The first of these goals has both short- and long-range implications while the second is restricted to the long-term by practical economic

*Technology Base R&D includes those programs funded in categories 6.1, 6.2, and 6.3A. The general criterion for defining Technology Base R&D is that it is directed at producing information that can be used in future engineering developments rather than in current developments (funded in 6.3B and 6.4 categories).

restraints. This current report, in responding to the Task Order, is intended to define the nature of the Technology Base R&D programs that would meet both of these goals, and then to review the current DOD Energy R&D program to highlight gaps and opportunities.

B. SCOPE

1. Energy Uses Considered

DOD energy use can be conveniently considered in three classes

- For aircraft, ship, and ground operations
- For fixed-base operations
- By industrial suppliers to DOD.

The first two of these classes are considered direct usage in the sense that DOD buys the fuel or energy needed for these uses, while the last is indirect since the fuel/energy used is purchased by the supplier. This report is concerned only with the first of these classes, i.e., energy use for aircraft, ship, and ground operations. As pointed out in the Part I report, this is the area where DOD relies heavily on its own R&D programs. The second and third classes were to be addressed in part three of the Task Order and are clearly more dependent on technology evolving from civilian R&D programs, but this part of the study has been cancelled.

2. Possible R&D Impact

The Task Order instruction to ". . . survey the possible impact . . . of R&D programs related to fuel options" is addressed by seeking answers to these questions:

1. What are the restraints on fuel options because of performance degradation, safety compromises, or direct costs?
2. What are the possible advantages of extending fuel options within these restraints?

3. What R&D work is needed to widen fuel options where it appears advantageous to do so?

The information developed throughout the report is directed at these questions. The results are collected and summarized in the Summary and Conclusions, subsection E--Conclusions and R&D Implications (p. xii).

3. Time Framework

The question of when the R&D impact could be felt is guided by the following definitions of time scale:

1. Near-Term (to 1990)--In this time period nonnuclear military vehicles will continue to be fueled primarily by currently marketed petroleum fuels. Possibilities in extending fuel options will be limited to: (i) fuels derived from natural crudes (military or civilian), (ii) minor engine modifications designed to broaden multifuel capabilities among these fuels, or (iii) acquiring and distributing information on the effects of usage of non-spec fuels in military vehicles.
2. Mid-Term (1990-2000)--Fuel options may be broadened in this time period by: (i) the possible availability in commercial quantities of liquid petroleum products from syncrudes (i.e., oil derived from coal or shale*), (ii) the possibility that engines incorporating major modifications to accommodate multifuel needs could be available.
3. Long-Term (beyond 2000)--Beyond 2000 further broadening of fuel options must be considered possible by: (i) conceivable availability of alternative fuels (such as hydrogen), (ii) conceivable development of new types of engines (such as lightweight nuclear engines).

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*As noted on page 18, there is a possibility that dedicated plants could provide significant quantities of synfuels to the military earlier than 1990.

While the specific choice of dates in this framework is somewhat arbitrary, it is clear that there is a significant change in options with time arising from the time necessary to develop and deploy either a new or modified fuel or engine, and this situation must be accommodated in the study. The three time periods chosen are convenient for consideration of R&D work related to fuel options.

4. Other Constraints

The following additional assumptions and limitations are to be noted:

- It is assumed that DOD will in general continue to follow a policy of relying on civilian production sources for fuel supplies. In some aspects this is a vulnerable position but there are actions that DOD can take to minimize the risks as will be discussed below.
- It is assumed that the military will continue to pursue a fuel standardization policy as a means of simplifying logistics problems.
- The study will be confined to fuel options that would have an appreciable impact on major uses, i.e., specialty fuels used in limited quantities will, in general, not be considered.
- It is taken for granted that the prime military goal is maintenance of fighting capability. Any fuel options must be examined on the basis that degradation of performance will not be acceptable except possibly in emergency situations.

C. ORGANIZATION OF THE STUDY

The overall question is how may Technology Base R&D programs on fuel options impact DOD's future energy management problems. We address this question by first looking at current DOD practice in procuring and using fuels. This is done in

Section II, "Background on Fuels for Military Vehicles." Section III, "Multifuel Engine Possibilities," then looks at the possible advantages and disadvantages of extending the capability of current military vehicles to use a wider range of petroleum fuels. This is followed by an examination of the problems associated with synthetic petroleum fuels in Section IV. In terms of the time scale defined above, Sections II, III, and IV examine the near-term and the mid-term possibilities. In Section V, the time horizon is extended to the far-term by considering the feasibility of military fuels other than liquid hydrocarbons for force operations. In each of the Sections, the R&D implications of the conclusions that are reached are stated as they arise. These are collected and summarized in the Summary and Conclusions at the beginning of this report.

D. DEFINITIONS

The following definitions are given for the convenience of the reader.

Petroleum Fuels--Liquid hydrocarbon fuels derived from natural crude oils.

Syncrudes--Refinery feedstocks derived from shale oil, tar sands, or coal.

Liquid Hydrocarbon Fuels--Fuels derived from either natural crudes or syncrudes.

Alternative Fuels--Fuels other than liquid hydrocarbons.

Multifuel Capability--The ability to use fuels other than the milspec fuel for which the engine was designed. There are two levels of multifuel capability--a narrow range that would allow use of civilian fuels of equivalent distillate range and specific gravity but not meeting other military specs (e.g., freezing point), and a wider range that would permit use of fuels of different distillate ranges (e.g., gasoline and diesel fuel, or diesel fuel and residual oils) in the same engine. In general, in this report, multifuel refers to the narrower range. Where the wide range is intended, it will be so stated.

II. BACKGROUND ON FUELS FOR MILITARY VEHICLES

A. CURRENT REQUIREMENTS

The military requirements for petroleum products are given in summary form in Table 1 for the years 1949-1976. Detailed requirements for the year 1973 are given in Table 2. Figure 1 provides some background as to the general boiling range and product yields of these materials from a "typical" barrel of crude oil; refinery processing, however, can greatly alter the yields shown, and the crudes vary widely in characteristics.

Note from Table 1 that the principal military liquid fuel used is jet fuel, constituting over 60 percent of the total requirements. Some 20 percent is for distillate fuels (diesel fuel and heating oil), and the remainder is for gasoline and residuals. The military have relatively little requirement for motor gasoline, in contrast to the civilian market wherein, as shown in Table 3, automotive gasoline is the largest volume item. The military requirements in FY 1973 are also listed in Table 3, and the ratio shown to domestic demand for the several categories for illustrative purposes; as some of the military fuels (particularly jet naphtha) were purchased outside the United States, however, and as FY 1973 was not a typical year (part limited war, part peacetime), the ratios shown do not have great quantitative significance. Nevertheless, it is clear that jet fuel requirements of the military are both substantial in quantity and represent a major fraction of the total U.S. production. These requirements, if obtained domestically under conditions of restricted crude supply (embargo or war) or increased demand (protracted general war), could potentially cause disruptions of

TABLE 1. MILITARY PETROLEUM REQUIREMENTS (Ref. 1)
(Deliveries from industry to consuming units, in thousand of barrels per day)

Fiscal Year	Motor Gasoline	Aviation Gasoline	Jet Fuels	Distillates	Residual Fuels	Total
1949	44	65	7	49	163	328
1950	49	63	10	59	163	344
1951	44	96	30	47	178	395
1952	60	121	44	58	170	453
1953	58	132	82	66	189	527
1954	55	129	118	66	178	546
1955	54	114	179	55	166	568
1956	45	119	218	55	154	591
1957	52	113	262	67	166	660
1958	42	91	259	63	143	598
1959	45	130	327	64	173	739
1960	45	101	323	67	156	692
1961	47	96	342	74	163	722
1962	49	102	378	79	180	788
1963	47	96	379	88	163	773
1964	39	84	396	86	179	784
1965	40	81	415	79	186	801
1966	42	73	443	85	231	874
1967	44	69	557	93	239	1,002
1968	49	60	621	97	248	1,075
1969	46	59	638	105	242	1,090
1970	44	44	544	97	190	919
1971	40	34	505	87	159	825
1972	35	27	488	122	125	797
1973	30	19	479	122*	98*	748
1974	21	13	341	105	83	563
1975	21	10	348	115	47	541
1976	18	6	314	108	36	482

*Reflects conversion of naval vessels from heavy fuel oil to distillate bunker fuel.

TABLE 2. BULK FUELS USED BY MILITARY SERVICES (Ref. 2)

Federal Stock No.	Nomenclature	Military or Federal Specification	ASTM Specification	Barrels Procured for Military Services FY73			
				Air Force	Army	Navy	Total
Aviation Gasolines							
9130-179-1125	Grade 115/145		D-910-67	7,499,294	121,935	2,022,826	9,644,055
9130-179-1122	Gasoline, Aviation, Grade 100/130	MIL-G-5572	D-910-67	146,339	11,666	428	158,433
9130-160-1839	Grade 80/87		D-910-67	1,003	4,761	26,435	32,199
Jet Fuels							
9130-256-8613	Grade JP-4	MIL-T-5624	D-1655-8	164,122,154	438,809	7,790,263	172,351,226
9130-273-2379	Grade JP-5	MIL-T-5624[1]	D-1655-8[2]	261,428	8,333	25,512,783	25,782,544
9130-551-2265	Grade JP-6						
9130-180-6385	Grade JP-7						
9130-NSL	Turbine Fuel, Aviation, Grade JP-8 (Kerosene Type)	MIL-T-83133	D-1655-8				
9130-854-0490	Referee for JP-4 Grade I	MIL-T-5161	D-1655-8				
9130-854-0491	Referee for JP-5 Grade II	MIL-T-5161	D-1655-8	1,309,432	49,255	27,812	1,386,499
9130-753-5026	Grade A-1	ASTM-D1655, Type A-1	Same				
9130-551-2264	JP-TS	MIL-T-25524					
Motor Gasolines							
9130-160-1818	Combat Type I	MIL-G-3056	D-439-68T	266,420	4,806,369	260,437	5,333,226
9130-160-1830	Gasoline, Automotive, Leaded, Combat Type II	MIL-G-3056	D-439-68T				
9130-264-4538	Prelium	FED-VV-G-76	D-439-68T	200,535	573,376	228,283	1,002,194
9130-264-6218	Regular	FED-VV-G-76	D-439-68T				
9130-160-1837		FED-VV-G-109	D-439-68T				
9130-142-9457	Research and Development	MIL-G-46015	D-439-68T	475,483	562,893	544,197	1,582,573
9130-543-6651	Limited Lead	(Spec.)	D-439-68T				
9130-172-8708	Gasoline, Automotive, No/Low Lead, Other, No/Low Lead, Premium	FED-VV-G-1690	D-439-68T	None	32,857	61,687	94,544
9130-167-6775	No/Low Lead, Regular	FED-VV-G-1690	D-439-68T	1,702,907	2,262,102	1,126,217	5,091,226
Diesel Fuels							
9140-273-2377	NATO Symbol F-75, DFM	MIL-F-16884		423,143	8,956,920	5,407,371	14,787,434
9140-286-5286	Grade DF-1, Winter	FED-VV-F-800	D-975-68	120,449	1,452,071	23,148	1,595,668
9140-286-5294	Diesel Fuel, Regular, DF-2	FED-VV-F-800	D-975-68	2,355,381	1,655,214	1,520,191	5,530,786
9140-286-5283	Arctic, DF-A	FED-VV-F-800	D-375-68	1,213,202	147,916	481,428	1,842,546
Fuel Oils							
9140-247-4366	Burner, FS-1	FED-VV-F-815	D-396-67	58,335	106,860	55,801	220,996
9140-247-4365	Burner, FS-2	FED-VV-F-815	D-396-67	1,721,067	7,457,949	1,951,717	11,130,733
9140-247-4360	Burner, FS-4	FED-VV-F-815	D-396-67	148,321	300,870	56,767	505,958
9140-247-4359	Fuel Oil, Burner, FS-5	FED-VV-F-815	D-396-67	463,675	704,034	479,468	1,647,177
9140-247-4354	Burner, FS-6	FED-VV-F-815	D-396-67	1,509,245	4,655,662	12,436,126	18,601,033
9149-180-6084	Diesel (MMS) DFS	AFPID 9140/1					
9140-181-7719	Burner, Low Sulfur FSL						
Kerosene							
9140-242-6748	Kerosene	FED-VV-K-211	—	120,733	105,812	86,865	313,410
Navy Distillate							
9140-145-0004	Fuel Oil, Burner, Navy Distillate	MIL-F-24397	—	7,380	None	24,395,444	24,402,824
Navy Special							
9140-256-8610	Fuel Oil, Burner, Navy Special	MIL-F-859	—	None	16,750	20,824,687	20,841,437

[1] Flash point to 140° F (minimum).

[2] Flash point to 110° to 150° F.

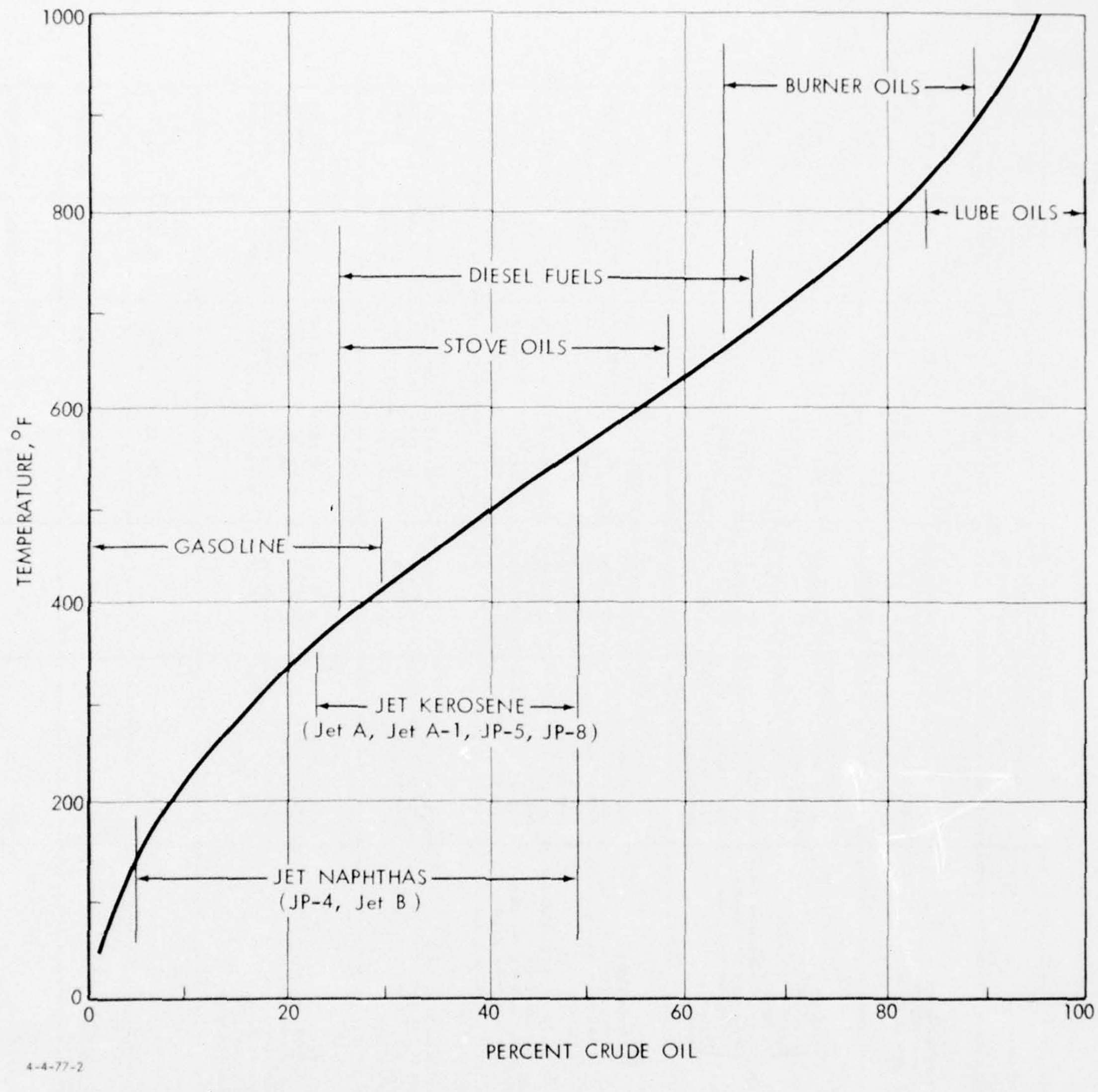

FIGURE 1. Proportions (Illustrative) and Approximate Boiling Ranges of Petroleum Products Processed from Crude Petroleum (Ref. 3)

TABLE 3. U.S. FUELS DATA FOR 1973 (daily averages, thousands of barrels per day)

<table>
<tr><th></th><th colspan="2">Domestic Demand[a] (Ref. 4)</th><th colspan="2">Fuels Used by Military[b] (Ref. 2)</th><th>Military Use / Domestic Demand (1973)</th></tr>
<tr><td>Gasoline, motor</td><td>6675</td><td></td><td>36</td><td></td><td>0.005</td></tr>
<tr><td>Gasoline, aviation</td><td>45</td><td></td><td>26.5</td><td></td><td>0.59[c]</td></tr>
<tr><td>Jet fuel, naphtha</td><td>217</td><td rowspan="2">1059</td><td>472[b]</td><td rowspan="2">543</td><td rowspan="2">0.51[d]</td></tr>
<tr><td>Jet fuel, kerosene</td><td>842</td><td>71[e]</td></tr>
<tr><td>Kerosene</td><td>216</td><td></td><td>0.9</td><td></td><td>0.004</td></tr>
<tr><td>Diesel fuel</td><td>749</td><td></td><td>65</td><td></td><td>0.087</td></tr>
<tr><td>Distillate fuel oils, excluding diesel</td><td>2343</td><td></td><td rowspan="2">212[f]</td><td rowspan="2"></td><td rowspan="2">0.041[g]</td></tr>
<tr><td>Residual fuel oils</td><td>2823</td><td></td></tr>
</table>

[a]Includes purchase by the military in the United States.

[b]Much of this fuel was purchased overseas.

[c]Almost all military aviation gasolines are 115/145 octane, for which little civilian market exists.

[d]According to Reference 2, the DoD jet fuel demand within CONUS was about 27 percent of U.S. production in 1973. Conservation measures have reduced military demand since that time (see Table 1) and in 1975 Military Use/ Domestic Demand was about 0.33.

[e]Reference 4 lists 68,000 bbl/day of JP-5 as daily average shipments in the U.S. in 1973; hence, JP-5 must be all, or almost all, produced domestically.

[f]Residual fuels, however, are quoted in Table 1 as 98,000 bbl/day, and distillates at 122,000 bbl/day for a total of 220,000 bbl/day. Diesel fuels, however, are included in distillates in Table 1, so the comparative total should be 212,000 + 65,000 or 277,000 bbl/day. The discrepancy may be due to differences between deliveries and consumption figures or other factors.

[g]If residuals are separated out and diesels and distillate fuel oils grouped together as in Table 1, then in 1975 Military Use/Domestic Demand was about 0.03 in distillates and about 0.02 in residuals.

the civilian aircraft industry (which is essential even in wartime). Certain specialty fuels, particularly 115/145 octane aviation gasoline, also merit attention, but it is jet fuels that are of greatest concern and will be given emphasis in the discussion here. Some discussion of theater effects and scenarios will be included but, in general, specific discussions of combat requirements will not be included. As a matter of interest, it is worth noting that the quoted defense fuel requirements for an unspecified general war are 1,600,000 bbl/day, about three times current consumption (Ref. 2).

In broad aggregate, the total U.S. military consumption in 1973 was 273 million barrels versus some 6.4 billion barrels for the total U.S. Total military consumption was thus about 4 percent of the total civilian consumption in 1973, and has dropped somewhat since (Table 1).

Returning to the jet fuel question, it should be noted that historically the principal (~85 percent of the total) military jet fuel has been JP-4, which is a quite different material from the U.S. commercial fuels,* Jet A and Jet A-1; JP-4 is primarily a heavy naphtha (with a formulation equivalent to about 2/3 naphtha and 1/3 kerosene), whereas Jet A (domestic use) and Jet A-1 (transoceanic use) are aviation kerosenes. The military (the Navy) also uses JP-5, an aviation kerosene, similar to Jet A-1 but specially formulated to give a high flash point for safety reasons. JP-4 has been used by the Air Force for supply and other (e.g., cold ground start) reasons. However, consideration is being given to adoption of a standard jet fuel known as

*Some Jet B, a civilian fuel similar to JP-4, has been used by commercial operators, particularly outside the United States, but usage is declining, primarily for safety reasons.

JP-8 for all but shipboard use. This fuel is essentially identical to Jet A-1, but with an anti-icing agent and corrosion inhibitor added. The specifications of these different fuels are shown in Table 4.

One of the arguments against the adoption of JP-8 has been the question of potential supply (and cost), it being argued that greater yields of JP-4 could be obtained from a typical barrel of crude than could JP-8*; however, a Bonner and Moore study (Ref. 6) appears to dispel this objection but this point needs further examination.** As a matter of fact, increasing competition for naphthas has in recent years (particularly during the oil embargo) led to difficulties in obtaining JP-4. JP-5, however, because of its special combination of flash point and freeze point requirements may indeed be in limited potential supply; some further study on this point, as well as confirmation of the Bonner and Moore results on JP-8, however, would be of interest.**

A rather different problem exists in the aviation gasoline area. The amount of aviation fuel used by the military is not large in absolute quantity. However, the military are essentially the only user of the 115/145 octane grade, and this material is becoming in short supply, partly because the demand is small and special processing is needed. The military are

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*Thus a chart in Ref. 5 gives percentage yields from a barrel of crude as being 2 percent as JP-5, 10 percent as JP-8 or Jet A-1, and 40 percent (max.) as JP-4; however, as yields vary greatly with crude source and refining techniques used, it is clear that the chart was intended to be more illustrative than quantitative.

**It seems self-evident that a shift by the Air Force to JP-8 would increase the demand for kerosenes, and thus the price of jet fuels for all users. The question is how much the prices would shift under current and projected supply conditions.

TABLE 4. FUEL SPECIFICATIONS (Refs. 7 and 8)

TYPE FUEL	JP-4*	JP-5	JET A	JET A-1	JP-8
SPEC MIL-T	5624	5624	ASTM 1655	ASTM 1655	83133
GRAVITY, SPECIFIC	0.751-0.802	0.788-0.845	0.775-0.830	0.775-0.830	0.775-0.830
GRAVITY, ^{o}API	45-57	36-48	39-51	39-51	39-51
DISTILLATION					
IBP ^{o}F	REPORT†	REPORT†		$\dagger$	REPORT†
10% EVAP MIN @	REPORT	400^{o}F	400^{o}F	400^{o}F	400^{o}F
20% EVAP MIN @	290^{o}F	REPORT			REPORT
50% EVAP MIN @	370^{o}F	REPORT	450^{o}F	450^{o}F	450^{o}F
90% EVAP MIN @	470^{o}F	REPORT			REPORT
EP MAX	REPORT	550^{o}F	550^{o}F	550^{o}F	550^{o}F
RESIDUE MAX	1.5	1.5			1.5
LOSS MAX	1.5	1.5			1.5
VISCOSITY -30^{o}F		16.5 MAX	15 MAX	15 MAX	15 MAX
FLASH PT MIN ^{o}F		140	105-150	105-150	105-150
FREEZE PT MAX ^{o}F	-72	-51	-36	-54	-54
WSIM MIN	70	85			70
THERM STAB ^{o}F	300/400	300/400	300/400	300/400	300/400
ΔP 5 HR	3.0 MAX	3.0 MAX	12.0 MAX	12.0 MAX	3.0 MAX
TUBE RATING	<3.0	<3.0	<3.0	<3.0	<3.0
RVP 100^{o}F	2.0-3.0				
HEAT/COMB BTU/LB MIN	18,400	18,300	18,400	18,400	18,400
A.G. PRODUCT	5,250 MIN	4,500 MIN			4,800 MIN
METAL DEACT	2 LB MAX	2 LB MAX	2 LB MAX	2 LB MAX	2 LB MAX
ANTI OXIDANT	8.4 LB MAX	8.4 LB MAX	8.4 LB MAX	8.4 LB MAX	8.4 LB MAX
SULFUR % WT MAX	0.4	0.4	0.3	0.3	0.4
RSH % WT MAX	0.001	0.001	0.003	0.003	0.001
CORROSION MAX	No. 1	No. 1	No. 1	No. 1	1B
GUM EXT MG/100 ML MAX	7	7			7
POT RESIDUE MG/100 ML MAX			14	14	
WATER REACT MAX	1B		1B	1B	1B
NEUT NO MAX	0.015	0.015	0.1	0.1	0.015
PARTICULATE CONTAMINATION	4.0 MG/GAL	4.0 MG/GAL	FREE OF	FREE OF	4.0 MG/GAL
FSII % VOL	0.10-0.15				0.10-0.15
LUMINOMETER NO.	60 MIN	50 MIN	45 MIN	45 MIN	45 MIN
SVI MIN	52				
SMOKE PT. MM		19 MIN	25 MIN	25 MIN	25 MIN
AROMATICS % MAX	25	25	20	20	25
OLEFINS % MAX	5	5			5
CORROSION INHIB REQUIRED	YES	NO	NO	NO	YES
EXPLOSIVENESS		50% MAX			
*IBP, typical, ^{o}F	140	360	--	335	314

†The specifications for Jet B are similar to those for JP-4. Boiling range and gravity range are identical. Jet B specifications permit a higher freezing point (-56^{o}F versus -72^{o}F) and slightly less sulfur (0.3% versus 0.4%). Other minor differences exist (Ref. 9).

considering phasing out the aircraft using this fuel grade, a point discussed in Section III below.

Turning now to the distillate and residual fuels, it would appear that the military portion of the total distillate cut is small enough so that supply problems, even in wartime, should be minimal, provided adequate information on use of civilian fuels were available, and equipments included any necessary adaptation for their use. Again, however, special military requirements, as for arctic diesel fuels, may not fit within this convenient argument. Specifications for diesel fuels are given in Table 5.

The aggregation of diesel fuels and distillate heating oil fuels in Table 1 implies the similarity of these fuels; indeed, as shown in Fig. 1, these materials overlap. In some areas of of the U.S. the fuels are (or once were) interchangeable (Ref. 10, p. 7-1). Diesel fuels and gas turbine fuels also overlap; in fact, a marine diesel fuel in use by the Navy is intended for both diesel and shipboard gas turbine use. In any event as shown in Table 3, it does not appear that military requirements for diesel fuels involve, or could involve, a major portion of the normal civilian supply potential. However, as noted above, civilian fuels can only be used if full information is available as to possible constraints in their use and/or if provision is made for their use by appropriate additions to the fuel systems. These points will be discussed further.

B. FUTURE REQUIREMENTS AND FUTURE SUPPLIES--SOME SCENARIOS

As indicated earlier, consideration of future supplies in specific terms is too complex an issue to enter into here. However, certain general points are worth noting, in an effort to put the remaining material into context. These relate to (1) the theater of operations (stored supplies versus continuing supplies, refining capacity available locally, and military versus civilian supplies and stores), and (2) the time frame

TABLE 5. FEDERAL SPECIFICATIONS FOR FUEL OIL, DIESEL

Properties	Values*				
			Grade DF-2		
	Grade DF-A	Grade DF-1	CONUS	OCONUS	Marine Diesel**
Gravity, °API	Report	Report	Report	32.9 to 41.0	Record
Flash point, °F(°C) min.	100(37.8)	100(37.8)	125(51.7)	133(56)	140(60)
Cloud point, °F(°C) max.	-60(-51)	1/	1/	2/	30(-11)
Pour point, °F(°C) max.	Report	Report	Report	3/	20(-6.7)
Kinematic viscosity @ 100°F.(37.8°C), cSt	1.2 to 2.5	1.4 to 3.0	2.0 to 4.3	1.8 to 9.5	
Distillation, °F(°C):					
50% evaporated	Report	Report	Report	Report	Record
90% evaporated, max.	550(288)	550(288)	640(338)	675(357)	675(357)
End point, max.	572(300)	626(330)	700(371)	700(371)	725(385)
Carbon residue on 10% bottoms, % wt., max.4/	0.10	0.15	0.35	0.20	0.20
Sulfur, % wt., max.	0.25	0.50	0.50	0.70	1.0
Copper strip corrosion, 3 hrs. @122°F(50°C) max. rating	3	3	3	1	
Ash, % wt., max.	0.01	0.01	0.01	0.02	0.005
Water & sediment, % max.	0.01	0.01	0.01	0.01	
Accelerated stability, total insolubles, mg/100 ml, max.5/	1.5	1.5	1.5	1.5	
Neutralization number, TAN, max.	0.05	--	--	0.10	--
Particulate contamination, mg/liter, max.	8	8	8	8	
Cetane number, min.	40	45	45	45	45

*VV-F-800B, 2 April 1975.

**MIL F-16884 G, March 1973.

1/ Limiting temperature value varies by state and within states, for each of seven coldest months. Satisfactory operation of cloud point set 12°F above the 10th percentile minimum temperature.

2/ DF-2 destined for Europe and S. Korea shall have a maximum limit of 9°F (-13°C). For other OCONUS areas, the maximum limit must be specified by the procuring activity.

3/ DF-2 destined for Europe and S. Korea shall have a maximum limit of 0°F (-18°C). For other OCONUS areas, the maximum limit must be specified by the procuring activity.

4/ The maximum limits do not apply for samples containing cetane improvers. In those instances, the test must be performed on the base fuel blend.

5/ This requirement is applicable only for military bulk deliveries intended for tactical, OCONUS, or long term storage (greater than six months) applications (i.e., Army depots, etc.).

over which synthetic crudes may enter the picture in a significant way.

1. Theater Effects

The earlier discussion relates primarily to military and civilian uses of liquid fuels in the U.S. during peacetime or limited war situations. The obvious question is to what extent such information is of value in a wartime situation in various parts of the world.

First of all, it would seem to be obvious that the military in a theater, such as Europe, where ground war has for many years been considered to be a possibility, will have stored fuel supplies in quantities deemed appropriate by the military commanders. Furthermore, in a highly industrialized area, such as Europe, which uses fuel at a rate approaching that of the U.S. (Ref. 4), there will be civilian sources of supply for at least some products such as diesel fuels, which, as in the U.S., would be large relative to military needs, and perhaps ample even with significant destruction of refinery capacity and interdiction of crude supplies. The jet fuel situation is more complex; refinery capacity for certain cuts, such as JP-5, or perhaps JP-8, may be limited; for lighter fuels, such as JP-4 (or Jet B), capacity should be fairly readily obtainable by, for example, cutting back on gasoline production. Refinery capacity for military jet fuels may in effect be increased by standardizing military fuels (JP-8 or NATO F-34) to specifications essentially identical to civilian fuels. At any rate, military commanders in these areas should be well aware of local refining capacity and, assuming some crude supplies can be maintained, should be able to capitalize on such production capabilities in wartime. In some cases (war or embargo), retention of multifuel capability (JP-4 or JP-8) would be important in terms of increasing supplies of jet fuels under limited crude oil supplies.

If conflict occurs in a less industrialized region, where stored fuels are not available, the problem becomes one of supply from established or safe sources. In a limited war situation, as in Vietnam, this supply problem should not be serious, unless accompanied by embargo, so that on-specification fuels should be obtainable.

There are, of course, many other scenarios. A massive nuclear exchange, for example, might leave combat groups who are still functional, but without logistic support, and who might find it necessary to "make do" with local materials. A situation might also develop in which long-term hostilities take place, from an area to which liquid fuel resupply is impossible, such as befell the Germans in World War II. In that conflict, propulsion systems operating on all sorts of fuels (pyrolyzed wood, manure, and, of course, gasoline from coal) were developed. Or, a remote island base conceivably could have nuclear power available, but no liquid fuels; in such circumstances, in theory, liquid fuels could be made, for example, from limestone or coral and water; ammonia could also be made, as was the concept in Army fuels programs some years back. Consideration of R&D for such contingencies is considered to be outside the scope of this effort.

2. Syncrudes

Syncrudes, their characteristics, etc., will be discussed at some length in Section IV. Here, however, it might be noted that "synthetic" crudes as, for example, from shale or coal, are not expected to be available in significant supply even in 1990, although dedicated plants might provide special fuels, such as JP-5, in amounts significant to the military at an earlier time. The ERDA "technology demonstration" plants are just that, and even if successful, will not be ready for large-scale installation for perhaps a decade. Older technology does exist for liquefaction of coal (Fischer-Tropsch, etc.), but no plans are

known to be under way to build such plants in this country. Thus, these sources may well be supplemental rather than primary refinery feedstocks until perhaps 1990; if so, they, like any new source of crude oil, would (after pretreatment, see Section IV) presumably be blended in with conventional petroleum feedstocks. This outcome is, however, by no means certain. In any event it should be recognized that beyond 1990 syncrudes may well become primary feedstocks, and since the life of any new military equipment from now on will extend into this time period, it behooves the military to evaluate now what the influence of fuels from syncrudes might be on military equipments. These matters are discussed further in Section IV.

C. IMPORTANCE OF FUEL SPECIFICATIONS TO THE SUPPLY QUESTION

As alluded to above, the obtainable yield of various fuels from crude oil is a matter of general interest at all times and becomes of critical importance during periods of restricted supply. Many factors enter into such questions, such as the availability of necessary refinery equipment (which is of interest to but somewhat outside the control of the military), the boiling range permitted, aromatics content allowed, etc., but particular specification variables, namely, freezing point and flash point, appear to have very great impact on supply (Ref. 11). Freezing point is particularly relevant if JP-8, a kerosene, replaces JP-4, a naphtha. The availability of kerosene-type fuels drops rapidly as the specification changes between about -30° F and -55° F freezing points. Thus it becomes a matter of considerable importance whether a freezing point specification of, say -54° F as in JP-8, -51° F as in JP-5, or -36° F as in Jet A is selected; indeed, JP-4 may necessarily be kept in the inventory if fuels meeting a -72° F (as with JP-4) specification are required. The freezing point question is not considered to be a well-settled one in terms of requirements (see, e.g., Ref. 12). A relatively high flash point requirement, coupled with its other specifications,

limits the supply of JP-5. Obviously, where supply problems are not serious, specifications should be set to meet the most extreme conditions ever encountered if costs are not seriously and adversely affected. In reality, however, very few military missions encounter the envelope of time, Mach number, and ambient temperature for which fuels having current specifications are required. Furthermore, it would appear that not all aircraft (high performance fighters, cargo planes, bombers) have the same fuel requirements. Additional study on these questions are called for; certainly under embargo or wartime situations, the freezing point specification, if it is as important as implied in Ref. 11, might well be relaxed. Fuel (or fuel line) heaters, of course, can also be considered.

D. IMPLICATIONS

The foregoing material has certain implications with regard to multifuel requirements, fuels handbooks accompanying military equipment, and R&D on synthetic fuels.

The principal military fuel is jet fuel. If military stores are proportioned according to projected requirements, the principal stored fuel would also be jet fuel; diesel fuel stores would be smaller in quantity. It would follow, based on this argument, that it is probably more reasonable to consider the use of jet fuel as a substitute for diesel fuel than the converse, the use of diesel fuel as an emergency jet fuel. However, if civilian stores are considered in an emergency to be part of the wartime inventory, it would seem that stored, or producible, diesel fuel might well be in much larger supply than jet fuel. On this basis, one might argue for investigation into the use of diesel fuel (or diesel fuel marine, already used in shipboard gas turbines) as an emergency jet fuel. Use of diesel fuel as a jet fuel in aircraft could involve problems in terms of combustion, plugging, freezing point, but these might well be resolvable with new atomizers, additives, etc., for limited

geographical areas. Thus, it seems reasonable to at least discuss the possibilities and resultant problems both for use of jet fuel in diesels and diesel fuels in jets.

The principal civilian fuel is, of course, motor gasoline; there are also large quantities made of home-heating distillate and residual fuel oils. One might ask, therefore, whether and what types of blends of gasoline with other materials, such as heating oils, might be of value as jet or other fuels in emergency military situations, and, again, what penalties might accrue. Similarly, home-heating oils might be usable to extend diesel supplies, as could perhaps some residual fuel oils.

We recognize that the military commander would probably view with considerable disfavor the need to carry out significant operations with "homemade" blends of various materials, or fuels which might freeze, or fail to relight at altitude, etc. Nevertheless, what does appear to be needed is a quantitative understanding of the interrelationships, problems, and potentialities of various possible fuels and fuel blends. "Fuels handbooks" are or would be extremely useful in this regard, if available, but some research and study are needed to generate an enlarged data base. The "fuels handbooks" should include some climatic data as well as time and Mach number envelopes by which a commander could evaluate the risk to aircraft (e.g., of higher freezing fuels) or ground vehicles in given regions of the world. There is also a need for simple diagnostic equipment for testing fuels in the field.

The same call for understanding applies to synthetic crudes and products derived therefrom. It is true that products derived from synthetic crudes (unless dedicated plants are built by the military) are expected to be a considerable number of years away, and presumably at that time, any products from these materials would necessarily meet the specifications of their civilian markets. Nevertheless, certain aspects of these

materials can be described which may be unique and do not currently involve specifications (e.g., shale-derived fuels tend to have appreciable nitrogen content, for which no specification is given). The same "handbooks" could well include any such pertinent information on these fuels; however, such data must first be amassed. A large part of this work could be handled under technology base efforts.

III. MULTIFUEL ENGINE POSSIBILITIES

A. INTRODUCTION

The U.S. Army has always had multifuel capability as a goal in order to minimize wartime logistic problems (Ref. 13). The Air Force and the Navy have not had this goal to the same extent in the past, but under the current petroleum supply situation it appears that increased emphasis on multifuel capability could be desirable* for all the Services. The general arguments that support this position are given in the previous section. The purpose of this section is to examine what the ranges of multifuel alternatives may be for military vehicles with respect to performance and maintenance problems.

The development of a wide range (see p. 5) multifuel engine capability could be expensive whether it be for ground or air vehicles, in the sense that they could be heavier (e.g., the LDS-465 multifuel diesel engine) or have higher specific fuel consumption. The engines, in general, could require extensive engine R&D, plus expensive qualification tests (especially true for aircraft) to validate satisfactory operation on a wide range of fuels. The assessment of the trades between expensive engines (and fuel systems) that could operate on a wide range of fuels versus less fuel-tolerant engines with better performance specifics is a difficult task to do in great detail. What we will undertake here is a general overview of the situation.

The basic criterion for modifying or developing new engines to have a multifuel capability must be to sacrifice combat performance only as a last resort. Combat performance is implied to include speed, range, and vehicle or crew vulnerability/safety.

*The fuel policy documented in Ref. 14 recognizes this need.

Vehicle economy, maintainability, life, environmental emissions, etc., should be sacrificed first.

In the past, multifuel capability was sought primarily for its advantages in a microenvironment. For example, the Army could simplify logistics in establishing a new combat area, if all the combat equipment had sufficient multifuel capability to operate on whatever military fuel might be available. Alternatively, the ability to use a number of fuels could provide flexibility to the local military commander by allowing use of captured or commandeered supplies. Other examples include the Navy aircraft that are operated from aircraft carriers which have a requirement to use JP-5 while at sea for ship safety considerations. When shore-based, the same aircraft use JP-4 because of its availability and relatively low cost.

In the future, multifuel capability is desirable and justifiable much more from a macroscopic viewpoint, i.e., large-scale disruptions of the fuel supply could require the utilization of other than the primary fuel for which a military vehicle is designed (see Section II). Hence increases in the fuel flexibility of military systems in the future would allow adjustment to abrupt changes in the large-scale fuel supply situation. Since the life of typical air or ground military systems may be 20 years or greater, large changes could occur in petroleum fuels availability and also in demands for particular refined products.* Hence a multifuel capability could allow military vehicles to use fuels that are most readily available at a reasonable cost. In addition, hydrocarbon fuels that are refined from other than crude oil in the future could tend to yield different amounts of distillate cuts than are available from crude oil; again flexibility could prove valuable.

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*That is, the demand for various cuts in the petroleum barrel can be expected to change during the life cycle of a military vehicle. A current example is the switch to low-lead gasoline in civilian consumption.

B. AIRCRAFT

In the past, the military have required fuels with very tight specifications for turbine engines. The approach was (1) to keep the logistics simple and (2) that the aircraft should be able to operate anywhere at any time, start under any conditions, have reasonable safety, and possess high performance. Thus one fuel (for example, JP-4) allowed most Air Force jet aircraft to operate from nearly any location in the world, at high flight altitudes and for long periods of time. When considered on a mission basis, there are many aircraft that do not operate all over the world or at extremely low ambient temperatures. As noted in Section II, relaxing fuel specifications where permissible could increase fuel availability. In this section we will briefly discuss some advantages and disadvantages that could accrue from more fuel-tolerant engines and fuel systems, and attempt to define the R&D needed to obtain increased fuel-tolerant military aircraft.

1. Piston-Engine Aircraft

The three military services standardized in 1961 on using 115/145 octane aviation gasoline (Ref. 15) in all piston-engine aircraft to simplify the logistics/supply problem. The primary reason for choosing this particular fuel was that a number of the large piston-engine aircraft (high fuel consumption) had high performance engines that were specifically designed for this fuel. In particular, these engines were the R-3350, R-4360, and in some cases the R-2800.* In 1973 military aircraft equipped with these engines consumed more than 90 percent of the total aviation gasoline consumed by military aircraft. To simplify logistics, lower performance aircraft were also adapted to operate on 115/145 aviation gasoline (but could be readily converted back to 100/130 gasoline).

*Reference 15, Enclosure 5.

Many of the piston-engine military aircraft requiring 115/145 aviation gasoline are with the Air National Guard, although there are sea-based Naval aircraft* that have high performance piston engines. Aircraft with engines specifically designed for the 115/145 fuel can be operated on lower rated fuels, with severe degradation in takeoff distance, takeoff weight, high-altitude performance, and high temperature performance.** Alcohol-water injection could possibly be added to some of these aircraft to maintain a large fraction of the takeoff performance; however, it is questionable whether it would be worth making this equipment modification for the remaining life of these aircraft. Most of the Army piston aircraft could reasily use the 100/130 octane that is commercially available today on a large scale This is because most of the Army's piston engine aircraft are very similar to existing civilian light aircraft.

At the same time when the military adopted 115/145 aviation gasoline, there were a number of large civilian aircraft with similar engines that had requirements for the same quality fuel. In succeeding years most of the civilian aircraft requiring 115/145 fuel have been phased out and replaced by turbine engine equipment. Hence the military aircraft consume nearly 100 percent of the 115/145 aviation gasoline manufactured in the U.S. at present. This consumption is relatively small in terms of total barrels per year (see Section II) and the petroleum refining industry is reluctant to supply this fuel since the

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*Reference 15, approximately 253 aircraft in 1974.

**Reference 15 (Enclosure 5) and Ref. 16 indicate that using 100/130 aviation gasoline could cause power losses up to 12.5 percent with water injection and 20 percent without injection, takeoff ground run increases up to 21 percent without injection, operation range degradation due to cruise requirement of rich mixture and retarded spark, gross takeoff weight reductions of up to 10 percent on sea level standard day (more at higher density altitudes), decreased rates of climb up to 15 percent, and possible decreased operating altitudes.

remaining civilian (general) aviation aircraft has standardized on 100/130 aviation gasoline. The 115/145 aviation gasoline requires high-grade blending stocks; hence, today it is competing with the unleaded auto gasoline for these particular stocks. For this reason fuel suppliers are not particularly anxious to supply the small demands the military has for these fuels.

Possible approaches to accommodate the short supply of 115/145 octane fuel include the following:

1. Phase out the aircraft requiring 115/145 octane as soon as practical (recommended by Ref. 15).
2. Convert to using 100/130 aviation gasoline and restrict operation of aircraft requiring the high octane fuel as discussed above. This would imply severe limitations on takeoff performance and reduced maximum gross take-off weights.
3. Restrict training and proficiency operations (i.e., Air National Guard operations) during short crude supply situations.
4. Use additives or blending agents to increase 100/130 aviation fuel to equivalent of 115/145. Reference 16 states that triptane plus tetraethyllead (TEL) has a performance number rating of 200/300. Thus a mixture of 15 percent triptane and TEL plus 85 percent 100/130 would yield 115/155 aviation fuel. It is possible that the military services could stock these high octane blending stocks (or additives) and add them to commercially available 100/130 aviation gasoline for critical aircraft operations that require extremely high performance. This approach should be investigated as it might provide the amounts of 115/145 fuel necessary for critical operations by aircraft such as carrier-launched anti-submarine aircraft. The additives/blend percentage could possibly be as low as 9 percent to meet the 145 rich performance number

requirement. In addition, since many of the aviation 100/130 performance number gasolines are now becoming low lead, there is a possibility that by blending additional tetraethyllead the performance number ratings could be raised to a higher (acceptable) level.

2. Turbine-Engine Aircraft

The Joint Commanders Technical Coordination Group on Fossil Fuel Standardization and Utilization (Ref. 14) is taking the position that all future land-based turbine-engine military aircraft should be designed to utilize JP-8.* They are also requiring that all the turbine aircraft in the future should be capable of operating on JP-4 through JP-5 (JP-8 is in between) without equipment modification or significant performance degradation. The Navy will be permitted to use JP-5 on shipboard. JP-8 is similar to the commercial jet fuel which is designated Jet A-1 plus additional anti-freezing and anti-corrosion additives.

Some of the fuel characteristics of JP-4, JP-5, and Jet A-1 (JP-8) that are particularly relevant in determining changes in aircraft performance are shown in Table 6 below (Ref. 18). Table 4 in Section II contains more complete fuel specifications. As can be seen from Table 6, the volumetric energy density of JP-8 (Jet A-1) is approximately 4 percent greater than JP-4 and approximately 1.6 percent less than JP-5. Thus volume-limited aircraft would have approximately 4 percent longer range using JP-8 versus JP-4. Note that the energy density per pound for JP-8 and JP-4 is nearly equal (even with allowable variations within military specification, the difference is less than 1 percent); thus weight-limited aircraft would suffer very small range of maneuver performance losses.

*Reference 17.

TABLE 6. SELECTED CHARACTERISTICS OF AVIATION FUELS

	Jet A	Jet A-1	Jet B	JP-4	JP-5	115/145
Specific Gravity Min.	0.7753	0.7753	0.7507	0.751	0.788	0.7026
Specific Gravity Max.	0.8299	0.8299	0.8017	0.802	0.845	Average
Freezing Point Max. °F	-36	-54	-56	-72	-51	-76
Viscosity at -30°F Max., centistokes	15	15		3[a]	16.5	
Weight Per Gal (Average)[b]	6.68	6.68	6.46	6.46	6.79	5.84
BTU Per Gal (Average)	122,912	122,912	118,864	118,064	124,957	110,376
BTU Per Lb (Average)	18,400	18,400	18,400	18,400	18,300	18,900

[a]No viscosity specification exists for JP-4. This value is from Ref. 10, p. 5-16.

[b]Average of fuel specification, not average of actual fuel procured.

Existing turbine-powered Navy aircraft already have the capability to use either JP-5 or JP-4 jet fuels. This requirement was instigated in original aircraft designs so that JP-5 (which is a relatively low-availability fuel) could be used for safety reasons when the aircraft is based at sea, while JP-4 can be used while land-based. It should be noted that Navy aircraft at sea do not have the low temperature starting problem that jet aircraft can have while land-based; hence the relatively high flash point and low volatility* of JP-5 do not create a starting problem while sea-based. Apparently altitude relight on JP-5 in Navy aircraft is more questionable than for Air Force

*As an indication of volatility, JP-4 has a vapor pressure of 2-3 psi at 100° F whereas JP-5 has a vapor pressure of about 0.04 psi (see Ref. 10, p. 5-13).

aircraft using JP-4. The energetic ignition source on Navy aircraft makes it possible to get high reliability of a relight by descent to altitudes of the order of 30,000 ft. The operators' manual for naval aircraft gives quite specific instructions on changing of the fuel control to accommodate change in fuel type. In most cases this can be accomplished with a simple screwdriver adjustment. Some Navy aircraft that are to be operated on JP-4 for an extended period of time require a retrimming of the fuel control to get optimum performance. In addition, with JP-4 (which is less viscous) the pilot is advised to watch for turbine blade overheating at maximum thrust settings. When the Navy aircraft are land-based, the combination of the easier starting on JP-4 plus the energetic ignition system of the naval aircraft ensures minimum starting problems at cold temperatures. Hence the Navy's turbine-powered aircraft are already multifuel to the extent that they can use JP-4, JP-5 and presumably any cut of distillate fuel between the two. Standardization on JP-8 fuel should, therefore, not create any problems or any additional qualification tests for existing Navy aircraft.

Most existing Air Force aircraft have been designed to use JP-4 and performance degradation (as described below) may be expected with other fuels. Air Force T.O. 42B1-1-14* specifies alternate** and emergency*** fuel for each of the turbine-powered Air Force aircraft. It is our understanding that due to insufficient funds most program managers have not completed any qualification tests of Air Force aircraft operating on other

*Reference 18.

**T.O. 42B1-1-14 definition: A fuel which can be used continuously with a possible loss of efficiency. The use of this fuel might result in increased maintenance or overhaul cost. Limitations of a significant nature such as reduced rate of climb, altitude, range, etc., properly place a fuel in the alternate category rather than in the emergency category. The applicable aircraft flight manuals should be consulted regarding operating restrictions whenever alternate fuels are used.

***T.O. 42B1-1-14 definition: A fuel which may cause significant damage to the engine or other systems, and therefore its use is limited to a one-time flight . . .

than JP-4. Existing Air Force aircraft have relatively low energy (intensity) ignition systems compared to those of Navy aircraft and the utilization of either JP-8 fuel or JP-5 fuel can present some problems (Ref. 19). The primary problem areas are ground starts at cold temperatures (Ref. 19 indicates that some aircraft will not start below 50° F on JP-5) and flameout/relight at high altitude. The Air Force apparently believes that qualification tests (which require substantial funds) would have to be run before most Air Force people in command positions would feel confident for sustained operations on either JP-8 or JP-5 fuel (Ref. 17). These tests would have to include cold-start and high-altitude relight studies. Based on the limited data that are available to us, most of the Air Force aircraft could have problems and probably would have to be retrofitted with (1) new higher energy ignition systems, (2) new fuel controls that would provide for easy selection of fuel type, and (3) possibly additional modifications to ensure high-altitude relight. Possible fixes to increase start potential and also the high-altitude relight capability could include development of fuel additives, development of systems to add gaseous oxygen during the starting phase, or heating the fuel before it enters the fuel control and engine combustor.

In addition, the Air Force is concerned that high-altitude, long-range, long-flight-time aircraft could have a freezing problem due to JP-8 having a freezing temperature of -54° F versus -72° F for JP-4. To counter this problem (the severity of which should be documented), research should be done on fuel valves that are more tolerant to freezing conditions, fuel cell fuel heaters, and/or additives to decrease the freezing point on particular missions that require temperatures lower than -54° F. This research should also include consideration of higher freezing fuels (such as Jet A, freezing point -36° F) for emergency use.

If it is desirable to be able to operate on a wider range of fuels in the future in aircraft, i.e., a wider range than JP-4

through JP-5, there are a number of areas where additional research and development should be accomplished. Some of these were brought to our attention in discussions with Mr. Churchill (Ref. 20) at the Air Force Aero Propulsion Laboratory. R&D on ground start and high-altitude relight is necessary for the heavier distillates (i.e., diesel fuel). Possibly new atomizer combustors and fuel additives would solve some of the problems.* In addition, the lubricity of the fuels can be important in the operation of fuel controls and other mechanisms in the aircraft fuel system. The approach generally taken in the past has been for fuel researchers to solve the problems by using additives. Churchill stated the opinion that improving the interface between the aircraft fuel system engineering and the fuels research might be productive. It is possible that use of fuels with less lubricity could be accommodated by improved design of the fuel system instead of by an additive.

Another problem that is of major concern for many high performance military aircraft is that the use of fuel in many heat exchangers as a cooling fluid requires that the fuel be quite stable to prevent thermal degradation. For example, diesel fuel is less stable and can cause fouling of heat exchangers. Thus more than just combustion is involved--the complete fuel system must be considered when new or different fuels are being considered for use in military aircraft.

Possible schemes requiring further research to improve altitude relight include using gaseous oxygen during starting, higher energy ignition sources, fuel heating, or additives during the start phase. The fuel additives are similar to adding

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*Blends of gasoline or naphthas with diesel fuels might also be of interest for some aircraft; these would presumably start more readily but if too much gasoline is present, would involve excess volatility. (JP-3, an earlier wide boiling range fuel, was discontinued for volatility reasons.)

gaseous oxygen except they change the fuel instead of the oxidizer. The Air Force uses 2 joules ignition systems while the Navy uses 5 joules or more. The cost to retrofit the Air Force aircraft would be $10,000-$15,000 per engine.

Most commercial airliners have fuel heaters ahead of the fuel control to condition the fuel, presumably to maintain good combustion efficiency. Churchill stated that fuel heaters ahead of the fuel control are a maintenance headache, but did not specify in what way. He also stated that fuel transfer valves in the B-52 wing tanks have presented problems with clogging by ice crystals. Possibly fluidics or fuel recirculation could be used to combat such problems.

NASA has been doing combustor studies using diesel fuel. These fuels contain 20 to 25 percent aromatics and have a lower smoke specification, i.e., from 20 down to 18.

In the case of Army turbine-powered helicopters, the problems are more severe in the sense that the engines are small, hence they tend to have a higher surface area to volume ratio which tends to promote coking (and other problems). Army turbine-powered helicopters should be capable of using nearly any fuel that is used by Army ground vehicles in the combat zone. Thus, these helicopters should be fuel tolerant to unleaded gasoline through diesel fuel* without major performance degradation (or excessive maintenance). The operators' manual for the AH-1 Army attack helicopter has a complete listing of primary alternate and emergency fuels. It states a limitation between engine tear-downs when emergency fuels have been used for a given period of time.

In summary, are a number of possible R&D areas worth pursuing to increase the multifuel capabilities of turbine-powered aircraft? Some avenues suggest that fuels research (i.e.,

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*High-altitude relight problems are not existent for Army aircraft.

additives, different blending components, etc.) could be an acceptable approach to solving some of the problems associated with being able to burn a wide variety of fuels. From the viewpoint of making the engines more tolerant, there appears to be work necessary on combustors using alternative fuels. Safety problems (fire hazards) should also be investigated.

Further investigations with the objective of determining the degradation of the engines and aircraft performance as a function of fuel type and time of usage should be performed. This type of information should be obtained for all Service aircraft and disseminated in the form of a handbook so that local commanders can make rational decisions whether to use an alternate or emergency fuel under given combat conditions.

C. GROUND VEHICLES

In this section, consideration will be restricted to combat and close support vehicles. This includes essentially all vehicles that have off-highway capability, either track or multiple wheel drive. As stated earlier, the Army has always had a goal of obtaining multifuel capability to optimize wartime logistics problems. The Army made the decision in the 1950s that all combat and close support ground vehicles of over 150 hp should have diesel engines (one of the candidate engines for the XM-1 tank is a 1500-hp turboshaft engine, which is an exception). The Army made this decision for the following reasons:

- Diesel engines provide low specific fuel consumption, hence yield maximum vehicle operating range with minimum fuel logistics load.
- Diesel fueled vehicles are less vulnerable because of relatively less fuel tankage (more fuel energy per unit volume), and diesel fuel is less hazardous from a fire viewpoint (high flash point).

- Diesel engines possess long life and have low maintenance requirements (in general).

Since the Army decided on diesel-powered vehicles and also established a goal of multifuel capability a number of years ago, there has been considerable effort devoted to developing multifuel diesel engines that will operate on fuels from motor gasoline through diesel or light heating fuel. Most research efforts on multifuel combustion in high-speed diesel engines have been conducted with this range of fuels because of the belief that there would be extensive gasoline supplies available (most aircraft at the time of the decision used gasoline); hence, there was a possibility of borrowing, capturing, or commandeering gasoline supplies in many combat zones. The lack of interest in heavier distillates and residuals was due to the problems of combustion in the short residence times available in a high-speed lightweight diesel engine (large low-speed diesel engines have used heavier distillate fuels for many years). The current fuel supply situation has encouraged the Army Fuels and Lubricants Laboratory (Ref. 21) to investigate burning of the heavier ends from petroleum, including the possibility of using unrefined crudes that have suitable properties.

The burning of the lighter distillates such as gasoline in a diesel engine is difficult from a number of viewpoints, namely, (1) ignition via compression, (2) high maximum pressures may be generated in a cylinder, and (3) high rates of pressure rise within the cylinder. These problems are not independent since the high ignition temperature of a volatile gasoline-type fuel delays ignition and allows more evaporation which then combusts rapidly after ignition occurs which in turn creates high maximum pressures and high rates of pressure increase in the cylinder increases the structural requirements and weight of the engine, and decrease the engine life. The most common approach to improving ignition on gasoline-type fuels has been to increase the

engine compression ratio, which severely increases the structural requirements of the engine. Hence the result of many multifuel diesel engine developments has been extremely heavy engines or somewhat low reliability.*

Now consider potential equipment modifications to increase the multifuel capability of existing diesel vehicles. Those modifications will be divided into two areas: (1) those that improve engine starting under adverse conditions and (2) those that improve engine operation, i.e., decrease maximum pressure and pressure rate. Some of these methods which may merit further Technology Base R&D will be described.

First, consider modifications that could improve the starting and light load operation of existing high-speed diesel engines. In the past, some military diesel engines, e.g., LD-465, LDS-465, etc., have used intake air heaters to improve the cold start capability, even using normal diesel fuel. To increase the start capability on other than diesel fuels, an automatically controlled intake air heater may be possible. This would involve developing a sensor that could estimate the cetane number of the fuel in the vehicle from measurement of the viscosity and density properties of the fuel. This cetane information, through an automated system, could then control the amount of fuel that is injected into and combusted in the intake manifold to heat intake air prior to entry into the combustion cylinders. Heated intake air increases the temperatures that are attained in the cylinder on the compression stroke, and thus assures ignition of high self-ignition temperature fuels such as gasoline. It may be feasible and desirable to operate such a system at light loads to ensure good ignition and combustion of low cetane number fuels.

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*Variable compression ratio piston engines have been developed. These are lightweight and may have value for future multifuel diesel engines. See Ref. 22, p. 100.

Another method that could have value for retrofit purposes is a system that would take a small amount of lubricating oil (from the crank case of the engine) and add this in a dispersed manner (spray) in the intake manifold. Past experimental research has indicated that a high cetane number additive, such as a heavier distillate or lubricating oil, creates many small ignition and/or combustion centers that promote combustion of low cetane number fuels. As an example, Blackburn (Ref. 23) stated that when they switched from diesel fuel to gasoline in the diesel engine that has been developed for the XM-1 prototype, it started readily down to -10° F on the gasoline. This should not have occurred from a compression temperature viewpoint, and they started investigating to determine the cause. They determined that there was enough diesel fuel being mixed with the gasoline from the fuel filters that had been used previously with diesel fuel to act as combustion centers. With new fuel filters the same engine would only start down to +20° F on gasoline.

Since small amounts of lubricating oil can increase the start capability on low cetane fuels, further research on other chemical additives that possibly could be blended with a universal fuel or gasoline to enhance ignition properties in a compression ignition engine may be advisable (see Ref. 24).

Another approach to improving the start capability on low cetane fuels would be to consider exhaust recirculation schemes (Refs. 22 and 25) during the start phase and/or partial blockage of the exhaust during the starting phase and low-load operation phase to prevent complete exhausting of the partially heated (via compression) air and partially chemically reacted fuel. Extensive quantitative knowledge of what such fixes could do to improve start capability on off-spec fuels is desirable.

Let us next consider potential retrofit equipment that could allow some of the existing diesel engines to operate on

off-spec fuels (primarily lower cetane fuels) without appreciable losses in some of the important performance factors such as torque and horsepower (which are essential for combat mobility) or decreased engine life. Most of the low cetane fuels have lower energy per unit volume and are less viscous than those with high cetane numbers hence the injectors not only inject less energy per injection (due to less BTUs per unit volume), but in addition inject less volume with the less viscous fuels because of injector leakage. Hence, power losses of 20 to 30 percent can occur as indicated in Fig. 2 (Ref. 26) when gasoline is used instead of No. 2 diesel fuel. In the LDS-465, a fuel density compensator was incorporated to increase the amount of fuel injected enough such that there was no reduction in torque and power.* The brake specific fuel consumption may be larger, but is probably acceptable for multifuel operation.

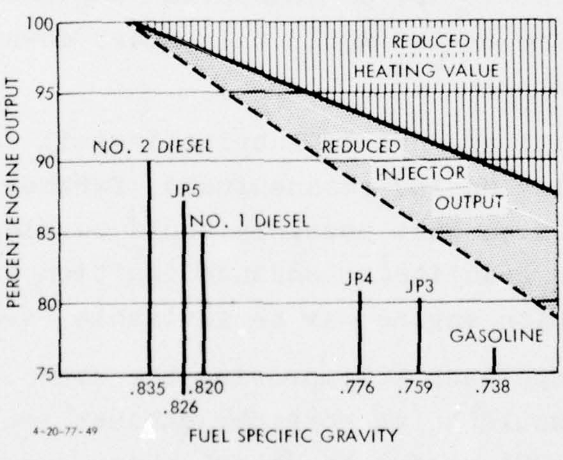

FIGURE 2. Effect of Specific Gravity, Viscosity, and Compressibility on Performance of GM Series 71 Multifuel Engine (Ref. 26)

The Army programs on classifying various crudes (Ref. 21) that could be used in high-speed diesel engines as emergency

*See Ref. 22, p. 180.

fuels may be of marginal value.* Many expensive tests to determine engine performance and life degradation are necessary. Alternatively, the use of available portable refineries (Ref. 27) to make acceptable diesel fuels could provide the necessary fuel availability in any conceivable war zones.

Let us now consider diesel engines for future combat vehicles. The diesel engine that has been developed as a candidate for the XM-1 tank has variable compression ratio pistons and uses high compression ratios for starting and light load operation. The high compression ratio (approximately 22:1) increases the temperatures on the compression stroke and hence it ignites a wider range of fuels. This approach should be considered in future multifuel engines to enhance starting.** In addition, the variable compression engines can develop extremely high hp/in^3 and hence decrease the pound-mass of engine per horsepower developed.

Preinjection of a small amount of fuel to give longer residence times for chemical reactions, and then injecting the main bulk of the fuel at a later time has been done mechanically in the past. It has not been too successful in the sense that it is difficult to accomplish, and expensive with a mechanical injection system. However, it has shown (Refs. 22, 24, 25) that preinjection can enhance the multifuel capability of compression ignition engines. Also, the rate of injection of fuel once one has a good environment for rapid combustion can change the pressure in a cylinder as a function of crank position, i.e., achieve a pressure-time distribution which yields more useful work per cycle. In addition, a volatile fuel-like gasoline, using the old methods of injection, has the time and the

*According to R.W. Ziem, ODDR&E, in a March 1977 comment, this program may not be continued.

**Intake air heating via combustion, as mentioned earlier, may also be desirable.

necessary environment to evaporate and form a combustion mixture which upon ignition burns at a very rapid rate which generates high maximum pressures plus high rates of pressure increase (both of which are undesirable characteristics). This requires very sturdy engines and decreases engine life.

Arguments can be made that there should be a large amount of research on better injectors and injection systems. There has been some in the past, but it apparently has not been seeded with the appropriate amount of capital. Improved injector systems, coupled with an automatic sensor system to determine the cetane number and density of the fuel, could control the amount of fuel preinjected, the time in the cycle as a function of RPM or speed that fuel is injected, and enhance the main bulk injection (faster injection) to increase the capability to combust low cetane fuels, and decrease the brake specific fuel consumption--even with normal diesel fuel. It is believed that this is an area that is not being pursued to the extent that it shoul be at present.

To obtain the technology to develop future compression ignition engines that are more capable of using a wide range of fuels, more basic studies on the combustion process in piston engines are needed, i.e., the influence of turbulence, the influence of fuel breakup and fuel injection timing, etc. With modern instrumentation and diagnostics, it is possible to do good basic combustion studies in the severe environments that exist in internal combustion engines.

The Army has been pursuing research and development on hybrid or stratified charge spark ignition engines of small horsepower for a number of years (Ref. 22, p. 343). A product of this effort, the Texaco Combustion Process engines, can burn a wide range of fuels while obtaining brake-specific fuel consumptions slightly less than small high-speed diesel engines (Refs. 21, 22, 25). The problems of obtaining synchronization of the air and fuel over a range of engine RPMs and loads, i.e.,

obtaining a near-stiochiometric fuel-air mixture near a spark plug, are formidable, as nearly 30 years of research indicates. Some of the other approaches to stratified charge spark-ignition engines as discussed in Ref. 21 lack appreciable multifuel capability. It is believed that the Army should concentrate on R&D on diesel engines with multifuel capability, due to the diesel advantages outlined in the beginning of this section.

D. OCEAN VEHICLES

The attainment of suitable multifuel capability in Navy ships presents fewer problems than for either aircraft or ground vehicles. In fact, the oil-fired steam turbines have already been converted from heavy oils to lighter diesels, and are capable of being converted back if necessary. Currently, according to Ref. 17, the Navy has a standardized marine diesel fuel* which can be used in all its propulsion systems including diesels and gas turbines.

The fact that ship operations do not have the same cold start requirements nor low freezing point specs as air or ground operations means that off-spec fuels can be used in marine diesels and turbines more easily without engine modifications. The problem is further eased in ships since vehicle performance does not degrade as rapidly with reduced propulsion power as it does in aircraft and in off-the-road vehicles. There is still a need to do testing to identify secondary potential problems (e.g., seals, storage, etc.).

These considerations lead to the conclusion that R&D on fuel options for military ship operations should be directed at these secondary problems rather than at problems which involve engine operation. Engine technology developed for Army use on multifuel diesels or for aircraft use on multifuel gas turbines may eventually be adapted to marine use, but there do not appear to be any compelling reasons to undertake such R&D work independently for use on ships.

*This fuel, DFM, is also equivalent to the NATO preferred primary ship fuel (NATO F-76).

IV. ALTERNATIVE LIQUID HYDROCARBON FUEL SOURCES

A. INTRODUCTION

Before discussing any of the details regarding alternative sources of liquid hydrocarbons, it seems desirable to put DOD's possible interests in these fuels into some perspective.

DOD's stated role in the synthetic fuels area is one of "incentivizing" (Refs. 1, 5), that is, of providing an incentive for the production of such fuels, as the reserves of such fuels are very large and fuels from them are invulnerable to embargo.* Incentivizing might mean guaranteeing product prices or subsidizing plant construction and, thus, could involve extensive commitments. For this reason alone, it would seem evident that DOD must be aware of the potential problems and possibilities with such fuels, and must undertake whatever

*Recoverable coal and shale reserves in the U.S. are given various numbers. One estimate for coal is 2 trillion tons (Ref. 28), which at 2 barrels or more of liquid fuels per ton, corresponds to 4 trillion barrels, or 10 times the known worldwide oil reserves. "Economically recoverable" reserves, which depend on coal prices, are much smaller but still enormous. The recoverable reserves of shale oil depends on the oil content assumed. The recoverable reserves given in the Project Independence Report (Ref. 29) are 610 billion barrels at 15 gallons per ton (or better), 243 billion barrels at 20 gallons per ton (or better), and 139 billion barrels at 30 gallons per ton (or better). Most of these higher quality reserves are in Colorado. The U.S. also has deposits of oil sands (or tar sands) in Utah, California, Kentucky, Mexico, and Missouri. These U.S. deposits (of heavy oil in sand) are much smaller than those in Canada, and poorly explored and have been of relatively little interest; nevertheless, the in-place oil volume is estimated to total more than 25 billion barrels (vs. Canadian deposits, which are being exploited, of 894 billion barrels)(Ref. 30). As perspective, the U.S. uses about 6 billion barrels of liquid fuels per year.

research is necessary to determine whether to make such commitments. Just how such synthetic fuels programs might develop, or whether Congress would permit DOD to "incentivize" in a significant way should DOD wish to do so, is unclear. In one sense, it would seem that such a role might be in conflict with the more general existing practice that DOD is to be a purchaser rather than a producer of fuels, and that DOD's fuels are to be as similar to civilian fuels as possible (Ref. 14). These general policies, coupled with a DOD R&D guideline (Ref. 5) which states that "DOD will not conduct R&D in quasi-military or civilian technical fields where U.S. civilian agencies have the primary responsibility and greater experience and knowledge," might be interpreted to imply a minimal DOD role in the synthetic fuels area. This, however, is apparently not the intent of Congress. Indeed, according to a January 1977 letter from Senator Wendell H. Ford to J. William Middendorf, II, the Secretary of the Navy, "recent amendments to the Naval Petroleum Reserves Act grant considerable authority to the Secretary of the Navy to develop Naval oil shale reserves and to seek to produce synthetic fuel." The letter specifically encourages DOD-ERDA projects in this area.

In more general terms, the military obviously must continuously examine and consider future fuels supplies, both in terms of availability and in characteristics. The military have special freezing point and flash point specifications not matched by civilian fuels. Also, in view of the usual lead times of 10 to 15 years needed for possible system modifications, synthetic fuels must be examined a decade or more before they become generally available, i.e., in the current time frame. Such fuels might in fact be available earlier if the policies alluded to above are implemented to build a synthetic fuels plant dedicated to military requirements. Such a plant would be of obvious value to the military, particularly under protracted conditions of restricted supply, where civilian demands

for non-dedicated fuels would impose severe pressure on the military. The military, of course, have available to them emergency powers that can be invoked under extreme circumstances.

B. GENERAL ASPECTS OF SYNCRUDE PRODUCTION AND REFINING

Fossil hydrocarbons exist in gaseous, liquid, semi-solid, and solid forms and in varying degrees of purity. Utilization of these materials generally requires both purification (refining) and transportation steps, both of which are important. (Thus, natural gas, a near-ideal fuel for heating purposes, was flared in Texas and Oklahoma before pipelines were constructed, and is still flared in Saudi Arabia.) The domestic energy problem is in large measure one of an impending change away from the more ideal of these various forms (natural gas, crude oil, and low sulfur bituminous coal) to the less ideal forms (high sulfur bituminous coal, coals of lower rank than bituminous, tar sands, oil shale) of which very large deposits exist, as noted earlier. It should be noted that the situation faced by the United States currently is similar in some sense to that perceived by the U.S. in the 1920s and again in the late 1940s. At those times, it was becoming increasingly difficult to find new domestic deposits of crude oil and much interest was evident in producing oil from shale, tar sands, and coal. Much of the available technology on shale, and at least some of it on coal, was developed in the early 1950s; however, discovery of large quantities of oil in Saudi Arabia about that time and its availability at low price made commercialization of such schemes impractical. Discovery of oil in Alaska in the 1960s also reduced private industry's interest in alternative oil sources.

It should also be noted that an extensive technology exists for the extraction, synthesis, restructuring, polymerization, and cracking of hydrocarbons, so that, if desired, liquid hydrocarbons of desired characteristics can, in principle, be made

from any carbonaceous material.* Thus the Germans in World War II found it necessary to produce gasoline from coal and did so (at considerable cost) via the Fischer-Tropsch and Bergius processes. South Africa has produced gasoline from coal ever since World War II via the Fischer-Tropsch process, for reasons of self-sufficiency (defense), and is currently substantially increasing plant output. China (The People's Republic), prior to discovery of large oil reserves in the late 1950s, produced a significant portion of its supplies from shale (Ref. 31). Many other nations [Scotland, Estonia** (now the Soviet Union), Brazil] have also produced, or are still producing, oil from shale; in fact, production of oil from shale in Scotland antedated by many years the discovery of crude oil in the U.S. (in 1869), so that the application of the adjective synthetic*** to oil produced from shale can be considered a historical misnomer (Ref. 33). The fact is that these alternative sources have been and can be exploited; they are, however, expensive to convert to a more convenient form, and cannot compete when crude oil becomes available in quantity at anything like its real production cost (which in Saudi Arabia has been estimated to be as low as 10 to 15 cents per barrel). The possibility that such

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*But the cost may be prohibitive except under the most extreme conditions.

**Some rich shales are burned directly for power generation in the Soviet Union.

***Note that the term "syncrude," as used by the National Petroleum Council, applies to a product meeting certain specifications, which could be fed to a conventional refinery (Ref. 32). Thus, raw shale oil is not a "syncrude," and must be distilled, coked, and hydrotreated to produce a syncrude; e.g., NPC "syncrude" from shale contains only .035 percent (350 ppm) nitrogen versus about 2 percent in raw shale oil; the pour point is also lower, 50° F versus ~85° F. See Section 4-C-2. It is not clear that the term still has this precise meaning, however, in actual usage.

oil supplies, which are known to exist in large quantities, might again become available at lower prices is, of course, a major deterrent to private capital investment in these alternative sources.* The environmental impact of mining solid materials from near the surface is also much larger than that from oil drilling, providing another major deterrent.

Two aspects of hydrocarbon deposits are of particular importance in determining their suitability as sources for refined liquid fuels: these are their hydrogen-to-carbon ratio and the quantity of undesirable materials (ash, water, sulfur, oxygen, nitrogen, metals) associated with a given mass of available carbon. Some figures of interest are shown in Table 7.

TABLE 7. PRODUCT AND RAW MATERIALS COMPARED, lb

	Typical Kerosene or Diesel Fuel	Typical Crude Petroleum (Ref. 3)		"Typical" Coal (Ref. 34)	"Typical" Shale (Ref. 35)
		Paraffinic	Naphthenic		
Carbon, basis	100	100	100	100	100
Hydrogen	16.2	16.6	13.3	7	13.5
Inert solids[a]	--	~0.1	~0.1	5-15	1000+
Water	--	?	?	10-50	10
Sulfur	0.05-0.1	0.1-0.4	0.1-5+	1- 5	0.7
Nitrogen	low	low	0-1	1- 2	2.5
Oxygen	--	0-4	?	14	1.6

[a]Salts, carbonates, silicates, vanadium, etc.

*For this reason, even small-scale production currently needs to be "incentivized."

Oversimplifying somewhat, the principal problem with producing oil from shale is the 1000 lb or more of solids that must be handled and disposed of for each 100 lb of carbon in the product, whereas the principal problem with coal is the need to roughly double the hydrogen content. In both cases, the non-ash impurities (nitrogen, sulfur, oxygen) must be removed, largely through hydrogenation processes. Surprisingly perhaps, the cost of doubling the hydrogen-to-carbon ratio in coal is at least equal to the cost of separating the oil from the solids in shale. [The hydrogen production and hydrogenation facilities in a preliminary H-coal plant design (Ref. 34) represent about half the capital cost.]

C. PRODUCTION AND REFINING OF PRODUCTS FROM OIL SHALE

Oil shales are rocks made up of inorganic materials (dolomite, quartz, clay, calcite, dawsonite, nahcolite) embedded in a three-dimensional organic polymer known as kerogen (Refs. 36, 37). Kerogen is essentially insoluble in organic solvents. To recover oil, the rock must be crushed and heated (retorted) to about 900° F; the kerogen decomposes and leaves as vapors which, except for light gases, condense to liquid shale oil (Ref. 36). Because of the quantities of rock involved per unit of oil recovered, efficient heat exchange is necessary; various processes have been developed to accomplish the heat exchange and to recover the evolved oil. These processes can be categorized as above-ground processes, which are discussed in Ref. 37, and "in situ" processes, which are discussed in Refs. 38 and 39. Because of the serious environmental impact questions with regard to disposal of spent shale, increased research interest has been shown in in situ methods. In situ methods, however, may create a more serious air pollution problem than other methods (Ref. 40), and at least in Colorado, air pollution standards (SO_2)

present a barrier to large-scale ($\gtrsim$200,000 bbl/day) shale oil production (Ref. 40).*

The product oils recovered from the different above-ground shale retorting processes and from rocks of differing oil content tend to be similar in characteristics; however, differences in composition do occur with shales from different parts of the world (Ref. 41); and some processes, as for example, in situ processes, may produce a more thermally cracked product than others. Several analyses of shale oil are given in Table 8 (Refs. 41, 35, 32). An NPC "typical" analysis and an NPC "syncrude" are given in Table 9.

TABLE 8. SHALE OIL CHARACTERISTICS

Source of Shale:	Rifle, Colo. (Ref. 41)	Rifle, Colo. (Ref. 41)	Naval Shale Reserve, Colo. (Ref. 35)	Rock Springs, Wyo. (Ref. 32)
Retorting method	Gas Combustion	Union Oil	Paraho	In situ
Specific gravity	0.943	0.945	0.937	0.885
Sulfur, %	0.69	0.71	0.61	0.72
Nitrogen, %	2.13	1.89	2.19	1.41
Pour Point, ^{o}F	85	75	85	40

The gas combustion retorting process and the Paraho process are similar; the Union Oil process, however, involving a "rock-pump" concept, with upflow of rock, is significantly different from the other two. The shale oils produced are similar. The in situ process raw shale oil, and the raw oil described by the NPC as "typical" (Table 9) are lighter products, implying perhaps some heavy materials have been lost or thermally cracked.

* It should be acknowledged that this is a rather old reference in the current rapidly changing energy situation.

TABLE 9. TYPICAL PROPERTIES OF CRUDE SHALE OIL AND SYNCRUDE (Source: U.S. Energy Outlook: Oil Shale Availability, National Petroleum Council, 1973)

	Crude Shale Oil	Syncrude
Specific Gravity	0.887	0.796
Pour Point, °F	75	50
Sulfur, wt %	0.8	0.005
Nitrogen, wt %	1.7	0.035
RVP, psi	-	8
Viscosity, SUS at 100° F	120	40
Analysis of Fractions		
Butanes and Butenes, vol %	4.6	9.0
C_5-350° F Naphtha		
Vol %	19.1	27.5
Gravity, °API	50.0	54.5
Sulfur, wt %	0.70	<0.0001
Nitrogen, wt %	0.75	0.0001
K Factor	11.7	12.0
Aromatics, vol %	-	18
Naphthenes, vol %	-	37
Paraffins, vol %	-	45
350-550° F Distillate		
Vol %	17.3	41.0
Gravity, °API	31.0	38.3
Sulfur, wt %	0.80	0.0008
Nitrogen, wt %	1.35	0.0075
Aromatics, vol %	-	34
Freezing Point, °F	-	-35
550-850° F Distillate		
Vol %	33.0	22.5
Gravity, °API	21.0	33.1
Sulfur, wt %	0.80	<0.01
Nitrogen, wt %	1.90	0.12
Pour Point, °F	-	+80
850° F-Plus Residue		
Vol %	26.0	None
Gravity, °API	12.0	
Sulfur, wt %	1.0	
Nitrogen, wt %	2.4	

Crude shale oil as normally produced (in above-ground retorting) is high in pour point (75-85° F) and in boiling range (see Tables 9 and 10), and contains tar acids, tar bases, and neutral fractions. Crude shale oil is also black, waxy, and foul-smelling, with high viscosity as well as pour point and, because of its high content of unsaturated compounds (olefins and diolefins) is unstable in storage (Ref. 42). The heavier fractions also contain more aromatics and more nitrogen than the lighter fractions. Nitrogen must be removed before the material is fed into conventional refineries, as nitrogen is a potent poison for certain refinery catalysts. Nitrogen is also objectionable in that a major proportion becomes NO_x on combustion, making the meeting of NO_x emission standards more difficult. Arsenic, metals, and finely divided solids are also problems; most of the metals and the finely divided solids are left behind in the coking process, but arsenic, which is a poison to hydrotreating catalysts, is distributed throughout the boiling range, and must be removed by caustic washing or other technique (Ref. 43).

TABLE 10. DISTILLATION FRACTIONS FROM RAW SHALE OIL (PARAHO) (Ref. 35)

Distillation Fractions	Yield (Vol %)	Nitrogen Content (% by Wt)	Sulfur Content (% by Wt)	Component Analysis (Vol %) Saturates	Aromatics	Olefins
Up to C_5	0.5	--	--	--	--	--
C_5 to 350 °F (Naphtha)	1.9	0.66	0.82	61.5	17.0	21.5
350 - 550 °F (Distillate)	9.6	1.27	0.85	48.7	30.8	20.5
550 - 850 °F (Distillate)	44.6	1.56	0.64	55.2	44.8	--
850 °F (Residual)	41.6	2.66	0.58	6.6	93.4	--

No significant commercial production of oil from shale has taken place in the United States, although much work has been done (Ref. 37). A recent substantial effort (Ref. 35) resulted in the production of 9,956 barrels of crude shale oil, produced from 15,789 tons of shale in a 56-day run of a small (8-ft diameter) Paraho retort. The results of this work are described in the following paragrapns. In addition, it might be noted that in the 1955-58 period the Union Oil Company of California operated a 350 ton/day retort for extended periods, producing fuel samples for Navy evaluation. (Reports on this work have not been obtained.) At that time, some 15,000 barrels of shale oil were refined and product put into the commercial market by Union. Undoubtedly, there have been other evaluations as well, but no attempt has been made here to review these various and usually proprietary efforts.

Results from the refining of raw shale oil are presented in Ref. 35; however, to some extent the results presented there are believed to be misleading in that the refinery used was not well equipped to handle shale oil and the maximum yield of refined products was not obtained nor, in fact, seriously sought. The laboratory investigation by Montgomery (Ref. 42) of Phillips Petroleum Company is perhaps more representative of what results can be obtained, although refinery processes can be adjusted to provide any of a diverse range of products. The general scheme advocated by Montgomery involves recycle coking* and hydrostabilization at the retort site, followed by pipelining to a refinery near a marketing area. The oil would then be hydrodenitrogenated in one or more passes, fractionated, and those distillates requiring further nitrogen removal recycled for further processing. Presumably the stabilized denitrogenated products would be blended with other refinery streams for further processing or for sale.

*Current analysis favors hydrogenating the whole fraction.

The Phillips work is summarized in Table 11. Note that a C_5+ volumetric yield of 91.9 percent of the raw shale oil was obtained. This could have been further increased by additional cracking and hydrogenation of the 650+ fraction, although, in view of the cost of hydrogen, there is always a question whether it pays to do so.

TABLE 11. PHILLIPS REFINING DATA ON SHALE OIL (REF. 42)

	Yield, Vol. %, Raw Shale Oil	Specific Gravity	C/H Ratio	Pour Point, °F	N %	S %	O %	H_2 Consumed SFC/ bbl feed
Raw shale oil	100	0.937	7.80	75	2.2	0.61	1.5	--
Coker distillate, C_5+	85.5	0.893	7.46	40	2.0	0.54	1.2	--
Hydrostabilized, C_5+ product (120-900° F)	86.8	0.882	7.07	40	2.0	0.49	0.83	414
Hydrodenitrogenated fractions					PPM	PPM	--	1970
C_5 - 180°	3.7	0.679	--	--	10	110	--	
180 - 400	30.1	0.774	--	--	240	10	--	
400 - 650	41.3	0.837	--	-15	695	30	--	
650 +	12.9	0.850	--	95	100[a]	--	--	
Total	91.9	0.812	--	--	917	60	--	

[a]Basic N; total N not given. For the entire 400° + fraction, total N was 710 ppm and basic N 415 ppm.

The 400-540° F fraction obtained by Phillips was reportedly a satisfactory diesel fuel without further processing for use in the Chicago area, with a cetane number of 50.2 and a flash point of 210° F.

No attempt was made in the Phillips work to characterize a jet fuel fraction. It is of interest to note, however, that the volumetric yield of fuels in the Jet A boiling range (300-520° F) was evidently quite high. The 100-400° F fraction is in the right general region for JP-4. Without freezing point data, and information on other specifications, however, yields of jet fuels cannot be made from these data.

Gary Western refining results are shown in Table 12; an overall material balance is given in Table 13. Note that only 65.8 volumetric percent of crude shale oil was produced as liquid product (gasoline through heavy fuel oil). The JP-5 yield of 650 barrels (~6.5 percent) was only about half the predicted yield; furthermore, the freezing point was only -26° F versus a -51° F specification for JP-5 and -36° F for Jet A. The flash point specification of 140° F for JP-5 was met. Nitrogen content, for which no specification exists, was 960 ppm. The JP-4 produced had a freezing point (-91.3° F) below specification requirement (-72° max.), and was at the lower limit of specific gravity. Nitrogen content was 140 ppm. In neither the JP-4 nor the JP-5 did the heat of combustion quite meet specification values.

Aromatic content on JP-4 and JP-5 was within specification limits. Cetane number of diesel and octane number of the gasoline were satisfactory. Note that the nitrogen content increases with boiling point; the heavy fuel oil was essentially raw shale oil. More extensive cracking and refining of this fraction would have increased yield.

None of these products met specifications in all particulars and all would be expected to be unstable. Tests were nevertheless run on these products (Ref. 44); in general, no surprises resulted. Army engine tests showed unexpected valve damage

TABLE 12. PRODUCTS FROM REFINING SHALE OIL, GARY WESTERN RESULTS (REF. 35)

	Yield, Vol. %	Specific Gravity		Freeze[a] Point, °F		N %	S %	O %	C/H Ratio
		Actual	Spec	Actual	Spec				
Raw shale oil	100	.937	--	85(P)	--	2.19 PPM	0.61 PPM	1.4 PPM	7.38
Gasoline (97-385)	7.3	.741	--	--	--	30	--	--	
JP-4 (156-405° F)	4.6	0.7507	--	-91.3	-72(max)	140	13		
JP-5/Jet A (350-518° F)	6.5	0.806	--	-26	-51/-36	900	27		
Diesel fuel marine[b] (430-686° F)	19.7	.861	--	50(P)	20(P)	0.233	0.44		
Heavy fuel oil (505-1028° F)	27.8	.941	--	95(P)	15(P)	1.73	0.25		
Total	65.8								

[a]Pour point where (P) is indicated.

[b]Not all hydrotreated; true yield was 11.7 percent.

TABLE 13. PARAHO-GARY WESTERN SHALE OIL OVERALL REFINERY MATERIAL BALANCE (REF. 35)

Refinery Feed Materials	Quantity volume (bbl)	Quantity mass (lbs)
Crude shale oil	9956	3,263,258
Total	9956	3,263,258
Refinery output		
Gasoline	725	188,585
JP-4	454	119,156
JP-5/Jet-A	650	183,265
DFM/DF-2	1965[a]	602,139[a]
Heavy Fuel Oil	2760	908,929
Coke	2571 [b]	424,560
Off-gas		418,090
Flush (crude)	357	108,060
Crude Tank Heel	608	199,100
H_2O (from crude)	84	29,450
Total	10,174	3,181,334
Material Balance Completion (Percent)	102.2	97.5

(a) Diesel fuel produced but not hydrotreated

(b) Barrel equivalents

with gasoline, but the fact that the gasoline was not to specification reduced the significance of the findings.*

Recent study and refining efforts by Exxon (Ref. 45) and by Atlantic Richfield (Ref. 46) should also be noted. Both studies concluded that jet fuels can be made more readily (in effect at lower cost) from shale oil than from liquids derived from coal liquefaction processes.

D. PRODUCTION AND REFINING OF LIQUID FUELS FROM COAL

1. Discussion

As noted in Section IV-B, production of liquid fuels--primarily gasoline--from coal has a long and involved history, with many processes having been considered. In all processes the object is to break up the complex condensed carbonaceous structure, remove oxygen, nitrogen, and sulfur, and increase the hydrogen content.** The problem is to do so in the most economical way (incidentally varying with the particular coal, its coking properties, impurities, etc.). At one end of the scale is the Fischer-Tropsch process, the only commercial one known to be now in operation, in which the coal structure is completely destroyed by partial oxidation to carbon monoxide, with subsequent recombination with hydrogen, oxygen elimination, and polymerization to form molecules of desired length. In

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*A subsequent investigation indicated that the fuel may have been contaminated.

**Or at least what might be termed the net hydrogen content. Where oxygen, e.g., is present, as in coal, a corresponding amount of hydrogen can be considered essentially tied up as combined water, leaving less hydrogen for attachment to the carbon itself. The total hydrogen-to-carbon ratio in coal is similar to that in benzene which is, of course, a liquid, and a good ingredient for motor gasoline (although poor for jet fuels and diesels). The focus here on carbon-to-hydrogen ratio is a rather simplistic attempt to generalize some very complicated chemistry.

general, however, it is desired to salvage at least a portion of the existing C-H bonds in an effort to reduce costs. Generally, because of the low hydrogen content of the starting material, product oils tend to be aromatic rather than paraffinic, naphthenic, or even olefinic. These aromatic components can, of course, be catalytically hydrogenated, if desired, at additional expense. The various processes have been reviewed by Perry (Ref. 47), by SRI (Ref. 34), and by the Project Independence Task Force (Ref. 48). In all cases, large amounts of hydrogen are required. Again, no attempt will be made to review these processes here. The ERDA effort on synthetic fuels is or has been focused almost entirely on coal as a starting material, with a smaller effort devoted to shale, and that primarily to in situ retorting. ERDA demonstration plant programs in coal liquefaction and gasification, on the other hand, involve potentially several billions of dollars (Ref. 49). These programs will not appreciably increase the availability of fuels for a decade or more, since these plants are demonstration plants only. Commercialization is a possible subsequent step. As with oil from shale, many problems are evident, including the basic one of an inability to increase coal production at a significant rate (Ref. 50).

2. Recent Studies

Several recent studies are particularly pertinent with regard to the DOD fuels from coal question--particularly the jet fuels question; one of these by SRI (Ref. 34) has been mentioned, others, e.g., by Exxon (Ref. 45) and Atlantic Richfield (Ref. 46) should also be noted.* Both SRI and Exxon examined the various coal liquefaction processes, and both concluded the H-coal process to be attractive relative to other proposed processes, although Exxon also recommended the Synthoil process.

*The Exxon study also examined the desirability of producing jet fuels from shale and, in fact, recommended shale oil as a preferred route.

Both studies considered the coal liquefaction plant as being independent of power generation, or other coal usage, and thereby rejected the COED process, which produces liquids along with char; the latter is intended for utility fuel. Both studies also assumed the product of the coal liquefaction plant to be principally a syncrude, suitable for blending with other crude oils in a feed to a conventional refinery; SRI also considered the possible yields should a refinery be specially configured to maximize jet fuel yields.

SRI examined oil production via the H-coal process for two representative coals, one an eastern bituminous (Illinois No. 6) and one a western subbituminous (Wyoming Powder River). The analyses of these coals are shown in Table 14. Stream flows for 100,000 bbl/day of syncrude are shown in Figs. 3 and 4, and the properties (and comparative properties) of the syncrudes in Tables 15, 16, and 17.

Hydrogen consumption to produce syncrude is 16,000 to 21,000 SCF/ton of dry coal, or about 7,000-8,000 SCF/bbl of product syncrude. This corresponds to about 7 lb hydrogen/100 lb carbon, which implies a rough doubling of original hydrogen content (per unit of carbon). The product syncrude will also require additional hydrogen (about 200 SCF/bbl of feed) to convert syncrude to useful products. The cost of hydrogen is critical to product costs; with the SRI study implying considerable economies of scale. In 1965, with better feedstocks for hydrogen manufacture (Ref. 51) than coal, estimated hydrogen costs at 10,000,000 SCF/day (95 percent purity and 1,000 psig) were about 30¢/1000 SCF, which, of course, are without cost escalation for inflation, nor allowance for larger scale or improved technology. The syncrude plants required about 750,000,000 SCF/day, so that economies of scale can be expected. Nevertheless, if the 30¢/1000 SCF figure is used, costs of

TABLE 14. CHARACTERISTICS OF REPRESENTATIVE EASTERN AND WESTERN COALS (REF. 34)

	Illinois No. 6 Bituminous Coal			Wyoming Powder River Subbituminous Coal		
	As-Received	MF* Basis	MAF† Basis	As-Received	MF Basis	MAF Basis
Proximate analysis (wt%)						
Moisture	10			33		
Volatiles	32	36		29.7	44.3	
Fixed carbon	49	54		31.5	47.0	
Ash	9	10		5.8	8.7	
Total	100	100		100	100	
Ultimate analysis (wt%)						
Moisture	10			33		
Ash	9	10.0		5.8	8.7	
Carbon	62.7	69.7	77.5	45.7	68.2	74.7
Hydrogen	4.8	5.3	5.9	3.2	4.8	5.2
Oxygen	8.9	9.9	11.0	11.1	16.6	18.2
Sulfur	3.5	3.9	4.3	0.5	0.7	0.8
Nitrogen	1.1	1.2	1.3	0.7	1.0	1.1
Total	100	100	100	100	100	100
Higher heating value (Btu/lb)	11,000	12,200		7,800	11,680	

*Moisture free.

†Moisture ash free.

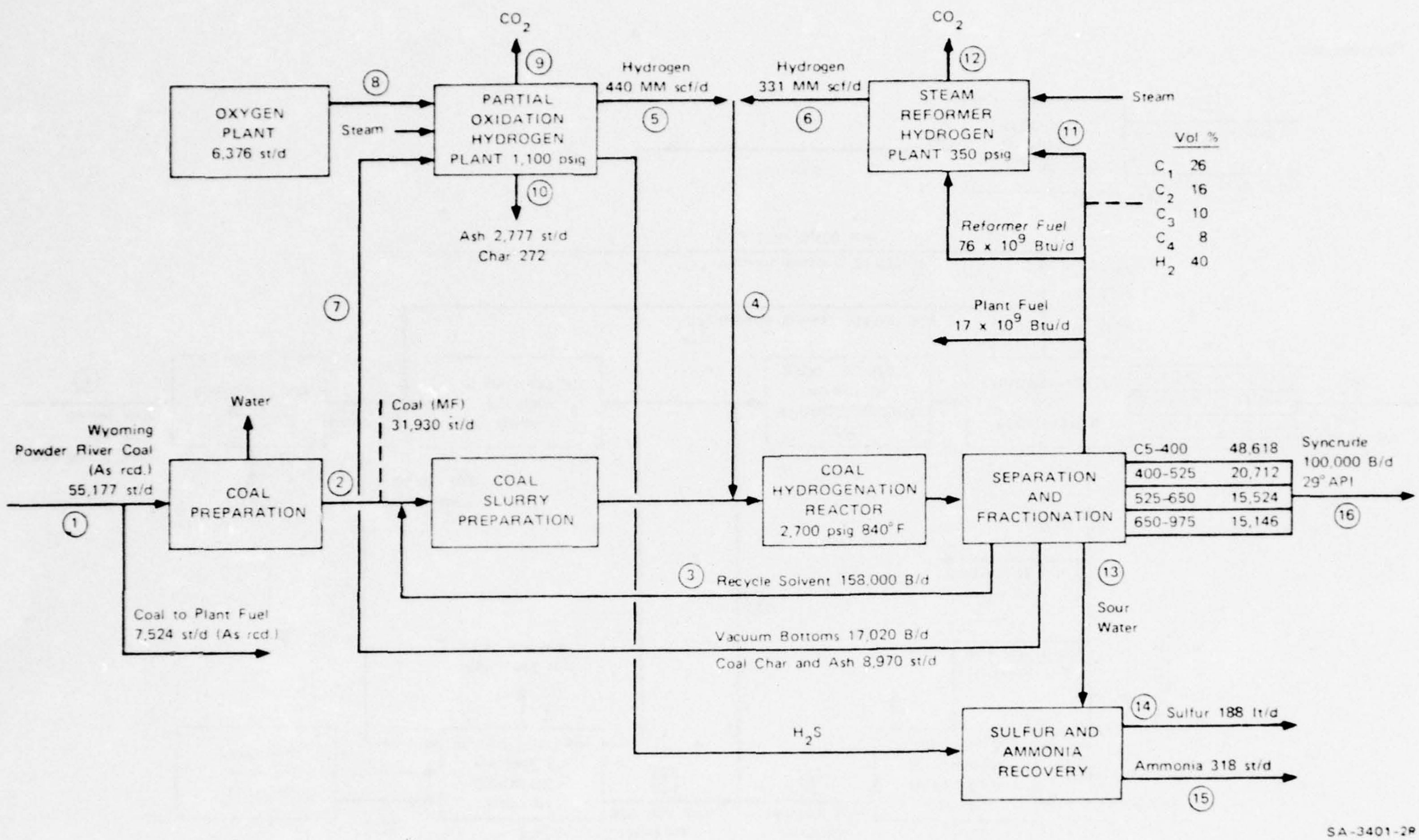

FIGURE 3. Flow Diagram for Syncrude from Wyoming Powder River Coal by the H-Coal Process (Ref. 34).

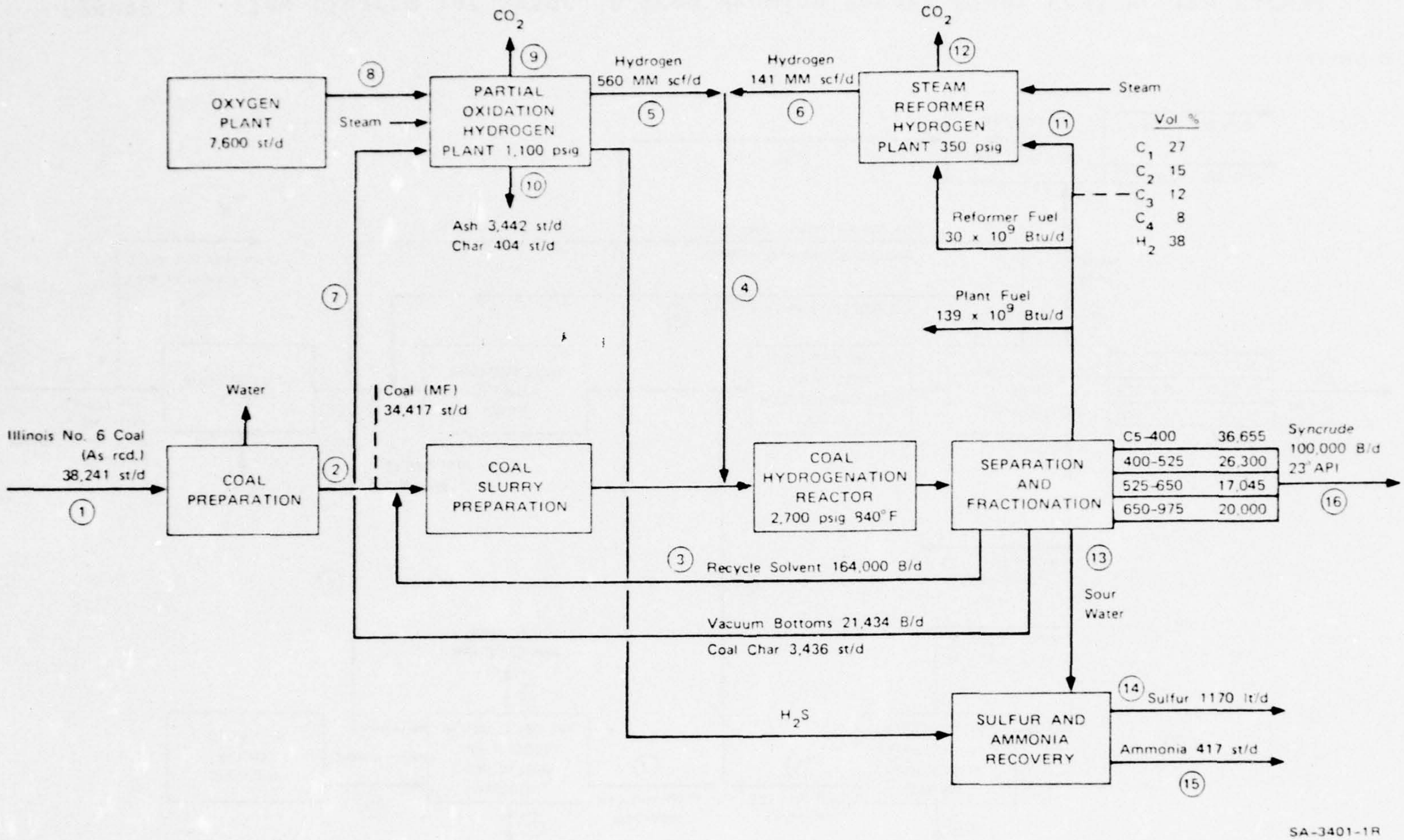

FIGURE 4. Flow Diagram for Syncrude from Illinois No. 6 Coal by the H-Coal Process (Ref. 34).

TABLE 15. PROPERTIES OF H-COAL SYNCRUDE FROM WYOMING POWDER RIVER COAL (REF. 34).

	Distillation Range				
	C_5-400°F	400-525°F	525-650°F	650-975°F	C_5+ Syncrude
Net yield (vol%)	48.6	20.7	15.5	15.2	100
Elemental analysis (wt%)					
Carbon	84.7	86.1	86.8	88.1	86.0
Hydrogen	13.5	11.6	10.3	8.0	11.6
Oxygen	1.6	2.1	2.4	3.2	2.1
Sulfur	0.08	0.1	0.13	0.2	0.11
Nitrogen	0.15	0.19	0.27	0.5	0.23
C/H ratio	6.27	7.42	8.43	11.0	7.41
Hydrocarbon type analysis (vol%)					
Paraffins	20	24	14	10	--
Olefins	--	--	--	--	--
Naphthenes	64	48	46	30	
Aromatics	16	28	40	60	
Gravity (°API)	48	27	19	8	29
Specific gravity	0.788	0.893	0.940	1.014	0.881
Weight (lb/gal)	6.56	7.43	7.83	8.45	7.32
BP midpoint	250	463	588	813	
UOP K-factor	11.36	10.92	10.75	9.94	

TABLE 16. PROPERTIES OF H-COAL SYNCRUDE FROM ILLINOIS NO. 6 COAL (REF. 34).

	Distillation Range				
	C_5-400°F	400-525°F	525-650°F	650-975°F	C_5^+ Syncrude
Net yield (vol%)	36.7	26.3	17	20	100
Elemental analysis (wt%)					
Carbon	85.3	86.4	87.3	88.9	86.8
Hydrogen	13.0	11.4	10.2	7.8	10.9
Oxygen	1.5	1.9	2.09	2.4	1.9
Sulfur	0.1	0.14	0.20	0.4	0.19
Nitrogen	0.15	0.15	0.23	0.5	0.23
C/H ratio	6.56	7.72	8.56	11.39	7.96
Hydrocarbon type analysis (vol%)					
Paraffins	12	13	15	5	
Olefins	--	--	--	--	
Naphthenes	65	52	37	20	
Aromatics	23	35	48	75	
Gravity (°API)	44	22	14	5	23
Specific gravity	0.8063	0.920	0.972	1.0366	0.9159
Weight (lb/gal)	6.7	7.65	8.09	8.62	
BP midpoint	250	463	588	813	537
UOP K-factor	11.04	10.60	10.49	10.42	10.91

$2.10-$2.40/bbl of syncrude result for hydrogen costs alone, whereas SRI gives total operating cost for the western coal case of $2.40/bbl of syncrude, excluding capital costs.

TABLE 17. COMPARISON OF NATURAL CRUDE AND H-COAL SYNCRUDE (REF. 34)

	Distillation Yields (volume percent)	
	East Texas Crude	H-Coal Syncrude[a]
Fractions		
C_5-400^o F (gasoline)	40%	37%
400-515 (kerosene)	14	26
525-650 (heating oil)	12	17
650-975 (fuel oil)	20	20
975+	14	
	100%	100%
Gravity, ^{o}API	38	23
Characterization factor	11.89	10.14
Sulfur, weight percent	0.33	0.19

[a]From Illinois No. 6 coal.

The SRI study indicated capital investment in the syncrude plant was almost identical for the two coal sources at about $7,000/daily barrel throughput. Roughly half of this is in the hydrogen facilities. These figures are based on the assumption that these plants exist independent of other sources; use of natural gas or naphtha to produce hydrogen would have greatly reduced the investment; use of coal as plant fuel or producing char as a by-product would also have reduced the investment. The SRI authors thought these alternatives to be unacceptable. The most important factor in product cost is coal cost; capital

costs are also a strong factor. Depending on assumptions made, syncrude costs were found to be $5 to $11/bbl, with the western coal case somewhat less expensive, largely because of the lower expected coal cost. At $10/bbl of syncrude, product costs were found to be $12-$13/bbl (as of November 1974).*

Cost estimates for syncrudes are difficult to nail down, and have escalated rapidly in recent years. Part of the problem is that world energy sources are interrelated; when the cost of petroleum is increased, the price of coal tends also to increase, as does the cost of labor, steel, etc., making for a difficult planning situation. These rapidly escalating costs have caused the abandonment of existing plans to increase production of crude from tar sands in Alberta. Shale oil commercialization efforts suffered similar cutbacks.

Coal is more widely distributed in the United States than is oil shale, providing one possible advantage in terms of product distribution. However, the large, presumably low-cost, reserves are in the West.

The SRI study contended that three 100,000 bbl/day syncrude plants, with refining optimized to produce jet fuel, could produce 136,500 bbl/day of JP-8. This approaches DOD's CONUS jet fuel requirement.

E. RECOMMENDATIONS

The future course of synthetic fuels production is unclear at the present time. As part of its defensive mission, it is clear that DOD must give serious consideration to the future course of the fuels it needs, and clearly to consider syncrudes as possible fuel sources. Both coal-derived liquids and shale oils are of interest in this context, although there

*Much higher costs have been quoted recently. (See, e.g., Ref. 52.)

are several reasons why DOD should take a more active role in shale oil than in coal liquids. These include:

1. Huge deposits of oil shales exist on Federal lands. Development of these resources would not be in conflict with private industry to the same extent that development of coal resources would be.
2. Product fuels from the coal liquefaction processes being pursued tend to be aromatic, thus making such fuels better components for unleaded motor gasolines or fuel oils than for either jet or diesel fuels. These aromatic fractions can, of course, be catalytically hydrogenated to naphthenes at additional cost; but it would seem preferable to permit the marketing of these synthetic products directly, relieving somewhat the demand for preferred cuts from the natural crude streams still available.
3. The nation's limited ability to increase coal production is already a matter of concern. DOD demands for such fuels would increase this pressure.
4. DOD already has carried out shale retorting, refining and end-use studies so that a valuable data base has been accumulated.

Certain technology base* efforts in the syncrude area are suggested.

Syncrude Fuels Evaluation. DOD should actively continue to monitor developments in the syncrude picture from both shale and coal. Further study and analysis, as well as bench scale, and pilot plant efforts on the properties of such fuels and the possibilities and costs for the production and upgrading of shale- and coal-derived fuels to jet and diesel fuels, would

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*Dedicated plants or other large-scale efforts are considered to be outside the scope of technology base efforts, which represent the principal objective of this paper.

appear to be appropriate. Such efforts, as in the past, must necessarily be coordinated with ERDA efforts.

Environmental Impact Studies. Many of these have been carried out, sometimes superficially. These should be carried out considering DOD interests, assuming plants to be located on Federal lands. Water supplies must be examined. The barriers and solutions as a function of production capacity must be developed.

Testing. Testing of products should be carried out, but not prematurely with severely off-specification fuels.

V. ALTERNATIVES TO HYDROCARBON FUELS

A. CANDIDATE ALTERNATIVE MILITARY FUELS

The discussion above has addressed the question of what possibilities may exist for DOD to maximize liquid hydrocarbon fuel options for its force operations. Consideration has been given to the range of possible hydrocarbon fuels that can be considered for general military use either now or in the future, to the potential availability of such fuels, and to their effect on military vehicle performance. All of this has been directed at the question: To what extent should DOD extend its petroleum fuel options? We would now like to turn our attention to the other question posed in the task order, that is, what options exist for DOD to reduce its dependence on liquid hydrocarbon fuels?* An initial screening of the possibilities in alternative fuels for military use can be made by considering the impact of different fuels on the <u>vehicle</u> performance and cost. Surviving candidates can then be assessed as to safety, handling, supply and cost problems.** This priority sequence results from the ground rule that military operational capabilities cannot be compromised. Thus, it will be assumed in the following discussion that if adoption of an alternative fuel results in either a decrease in performance or a significant increase in cost of the vehicle, then the alternative fuel is an unacceptable candidate.

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*See Definitions, Section I-D.

**It is of interest to note that considerations of civilian alternative fuels have cost and supply as the primary screening factors.

All military combat vehicles are high performance vehicles, which means that, compared to civilian transportation vehicles, a relatively large part of the vehicle is devoted to structural and propulsion system needs and a relatively small part to payload. The exact balance between the competing requirements of increasing performance (reflected in larger propulsion systems and stronger structures) and reducing cost (reflected in larger payloads) is determined during the vehicle design by numerous tradeoff studies. Typically, in military high performance vehicles, the end result is that the propulsion system is as large or larger than the payload, and hence, any change in weight or volume requirements of the propulsion system can have a large impact on the cost of the vehicle if performance (speed, range) are to be maintained (Refs. 13 & 53). This situation is different from that faced by the usual commercial surface transportation systems (e.g., trucks, ships, trains) where the payload is typically much larger than the propulsion system. The exception is long-range commercial air transports which have payload/propulsion system weight ratios that, at ranges over 3,000 miles, approach those of military high performance vehicles.

Whether the weight or volume of the propulsion system is of primary importance to the vehicle designer depends on the nature of the vehicle. Some vehicles are weight-sensitive others volume-sensitive.* We will call a vehicle weight-sensitive in this discussion if an increase in weight of the propulsion system would cause an equivalent decrease in payload carrying ability, if the vehicle size is maintained. The same definition holds for volume-sensitive if "volume" is substituted for "weight" in the previous sentence. Examples of weight-sensitive

*The terms weight-limited and volume-limited are frequently used but are avoided here because they are ambiguous.

vehicles are high flying aircraft and high-speed ships (hydrofoils and air cushion vehicles). On the other hand, low-altitude high-speed aircraft or missiles and fleet submarines are volume-sensitive. An unusual example of a volume-sensitive vehicle is a tank. Because the armored volume is the major factor in determining gross vehicle weight, the vehicle is much more sensitive to volume changes in the propulsion system than to weight changes. To a lesser extent the same is true for any armored ground vehicle.

Now let us consider more quantitatively the impact of a change in fuel weight in a weight-sensitive vehicle. If a new fuel is considered which causes an increase ΔW_F in fuel weight for the same range, then either the payload must be decreased or the vehicle must be increased in size to carry the same payload. In either case, the cost impact (in terms of vehicle procurement cost per pound of payload) is approximately

$$\frac{\Delta \$_V}{\$_V} = \left(\frac{\Delta W_F}{W_F}\right)\left(\frac{W_F}{W_P}\right)$$

where $\$_V$ = vehicle procurement cost per payload pound (excluding armament and other payload costs)

W_P = payload weight

W_F = fuel weight.

That is to say that the fractional change in vehicle cost for a given payload carrying ability is equal to the fractional change in fuel weight multiplied by the ratio of fuel weight to payload weight. This last factor is sometimes called the "growth factor" by vehicle designers.*

For example, in combat aircraft the fuel weight is typically equal to the payload weight. Hence any decrease in energy

*For a more detailed discussion, see Ref. 53.

density of the fuel will have an equal incremental effect on vehicle procurement cost, i.e., a 10 percent reduction in energy density will cause a 10 percent increase in vehicle cost. Similar arguments hold for vehicles that are volume-sensitive, except, of course, that the growth factor is expressed as a ratio of fuel volume to payload volume. As mentioned above, the tank is an example of volume sensitivity since the armor is over 40 percent of the gross weight and its weight is directly determined by the interior volume.

This background presents a rational way for screening the potential of other fuels to replace liquid hydrocarbons in the military vehicles of interest. Candidate fuels have been the subject of intensive study in recent times, particularly since the oil embargo, for all applications where liquid hydrocarbons are now used in both civilian and military vehicles (e.g., Refs. 54, 55). In all cases the advantages of using air as an oxidizer are so overwhelming that consideration is limited to fuels which can be used in air-breathing engines.* The list of candidates is given in Table 18 with some of their important properties. Examination of these properties in the light of the cost arguments above leads to these conclusions:

- The best fuels for general military use are the diesel and jet fuels currently in use.
- A viable alternative military fuel (from a performance and acquisition cost viewpoint) would be liquid hydrogen, but it could not be used on volume-sensitive vehicles.
- The other alternative fuels could possibly be used in some civilian vehicles which are not particularly weight- or volume-sensitive, and where the economic

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*In submarines, where an oxidizer must be carried, other fuel/oxidizer combinations may be useful. However, most military submarines are nuclear-powered.

impact is acceptable, but could not meet acceptable performance and acquisition cost impact criteria for military vehicles.

TABLE 18. PROPERTIES OF ALTERNATIVE VEHICLE FUELS (Source: Refs. 54, 55)

Fuel	Lower Heating Value 10^3 BTU/lb	10^3 BTU/ft^3	10^6 BTU of Fuel[a] Wt in lb	Vol in ft^3
Military Diesel or Jet Fuel	18.2	1020	54.9	0.98
Liquid Hydrogen, LH_2	51.6	229	19.4	4.37
Hydrogen as a Hydride, MgH_2	3.93	344	254	2.91
Ammonia, NH_3	8.00	341	125	2.93
Hydrazine, N_2H_4	7.20	454	139	2.20
Methane, CH_4	21.5	557	46.5	1.80
Methanol, CH_3OH	8.60	429	116	2.33
Mixed Methylamines, MMA	15.1	630	66	1.59

[a]Equivalent to approximately 8.8 gallons of a petroleum fuel.

Since the cost of petroleum fuels would have to increase several fold before alternative fuels could become economically feasible in the civilian market, it appears that the military will continue to use petroleum fuel even when in the long run supplies decrease and prices escalate to where syncrudes are economically viable. There are two possible exceptions to this scenario:

1. For vehicles that are weight-sensitive, and range-limited with petroleum fuel, there is a possibility

that liquid hydrogen could become a competitive military fuel.

2. Nuclear propulsion offers essentially unlimited range and hence may be used more extensively by military vehicles in the future.

In the next two sections these possibilities are examined in more detail.

B. LIQUID HYDROGEN AS A MILITARY FUEL

The vehicles for which liquid hydrogen (LH_2) could possibly be a cost-effective fuel are those in which extended range without refueling would have a large military payoff. In addition, of course, the vehicles must be weight-sensitive and not volume-sensitive. The general classes of vehicles that fit these specifications are long-range (or long endurance) aircraft, and long-range high-speed ships (surface effect ships or hydrofoils). Typical missions might be long-range air transport, sea control from land bases, or long-range bombing for aircraft. Since high-speed ships with petroleum fuels are currently limited to ranges of 1000 miles or less for acceptable payload fractions, any ocean-going high-speed ship needs a fuel with significantly greater energy per pound than liquid petroleum.

A major factor influencing whether LH_2 will ever become a military fuel is the question of whether the potential performance payoff is worth the added costs. This is the question to be addressed in the following discussion. First, it should be noted that there are some trends that make such an examination of current interest in the sense that if they accelerate appreciably, LH_2 could become an economically viable military fuel sooner than is generally anticipated. These trends are:

- The growing industrial use of hydrogen is creating larger sources of supply and costs may come down (Ref. 55).

- The projected mass production cost of LH_2 is still much greater than liquid petroleum, however, the ratio of LH_2 to petroleum costs will decrease as liquid hydrocarbon prices increase further and energy from coal and nuclear power becomes relatively cheaper* (Ref. 55).
- The continuing decrease in number of overseas bases is placing a higher value on the range capabilities of aircraft.

The energy-per-pound advantage of LH_2 is offset by two factors in actual vehicle designs. First, since it is a cryogenic liquid, tanks must be heavily insulated and adequate boil-off provisions must be made. Second, its low density requires very large storage volumes, which even in weight-sensitive vehicles can create appreciable structural weight and drag increases. There is extensive engineering experience in the problems of lightweight tankage arising from the NASA space program. Recently, a number of design studies of vehicles, using LH_2 as fuel have been made (Refs. 56 through 61) which utilize the latest storage and handling technology. The results of these studies can be summarized as follows:

- For supersonic aircraft applications, the weight advantage of LH_2 is greatly offset by the drag and structural weight increases needed to accommodate the increased volume. Study results vary in the amount of the projected range or payload benefit from marginal to significant.
- For subsonic commercial aircraft with ranges of less than 3000 miles, the benefits appear in reduced weight and power of the aircraft needed to carry a given payload. Whether there is an overall economic gain depends

*Alternatively, cheaper H_2 could be used to synthesize liquid hydrocarbons, so LH_2 may never become as cheap as liquid hydrocarbons.

strongly on the projected cost of the LH_2 fuel. As range is increased beyond 3000 miles, the positive benefits increase quite rapidly but there is not a great commercial demand for very long-range aircraft.

- For high-speed ships, it is concluded in Ref. 58 that weight benefits from LH_2 fuel are completely offset by increased structural requirements for the larger volume vehicle that is needed. This is a somewhat surprising result, which appears to reflect that the structural weight of the ship is determined by factors other than the density of its payload.
- For military air transport, the conclusions in Ref. 61 with respect to the impact on the vehicle agree with the commercial aircraft studies, i.e., the benefits are marginal when the high cost of LH_2 is included for ranges up to 3000 to 3500 miles; but at longer ranges the benefits in payload-carrying ability grows rapidly. Since the military air transport requirements are dominated by emergency resupply of Western Europe, and long-range needs are relatively small, the use of LH_2 does not show enough benefit to offset its supply and handling problems.

The general result of all these studies appears to be that for military use LH_2 offers more problems than its benefits would warrant, and for commercial use the timing of LH_2 use in transportation will be determined by when the price spread between LH_2 and liquid hydrocarbon fuels narrows. A rational course of action for military usage appears to be to wait until LH_2 comes into commercial transportation vehicle use before seriously considering it as a possible military fuel. This seems to be the current thinking. The one factor that might change this scenario is a strong demand for very long-range aircraft. As noted above, there are signs of such a demand developing so it may be of interest to assess the benefits that LH_2 can produce in payload-carrying ability for very long-range aircraft.

A comparison of the cost of carrying a payload to long ranges with a conventional subsonic jet-powered aircraft, alone, with such an aircraft accompanied by a refueling tanker aircraft, and with an LH_2-fueled subsonic jet aircraft is shown in Fig. 5. The method of analysis is taken from Ref. 53. The weight and drag penalties associated with LH_2 tankage requirements are approximated from the studies of Brewer (Ref. 56). The refueling situation is approximated by assuming two identical aircraft, one of which carries fuel only, both originating at the same base. The cost scale is taken from the approximations used in Ref. 56. The results given, though approximate, can be used to estimate the benefits in vehicle procurement cost as a function of range. The point is that if there is a large enough demand for long-range aircraft (i.e., beyond 5000 to 6000 miles), then the procurement cost benefits will more than offset the fuel cost and handling problems.

C. R&D IMPLICATIONS

In view of possible increased interest in long-range military aircraft, it would appear wise to keep the option open for use of LH_2 in aircraft by continuing programs in the technology base.* The following studies are recommended:

1. General Vehicle and System Studies. Available studies are not conclusive as to the potential value of LH_2 in extending aircraft ranges. It would be useful to establish the tradeoff between range demands and fleet costs (including refueling) for large military transport aircraft using either LH_2 or jet fuel or possibly both.
2. Logistic Studies. A major military need is to have an assured supply of fuel. It may be feasible for the

*The current trend is to phase out such efforts in military R&D. NASA, however, has a continuing program.

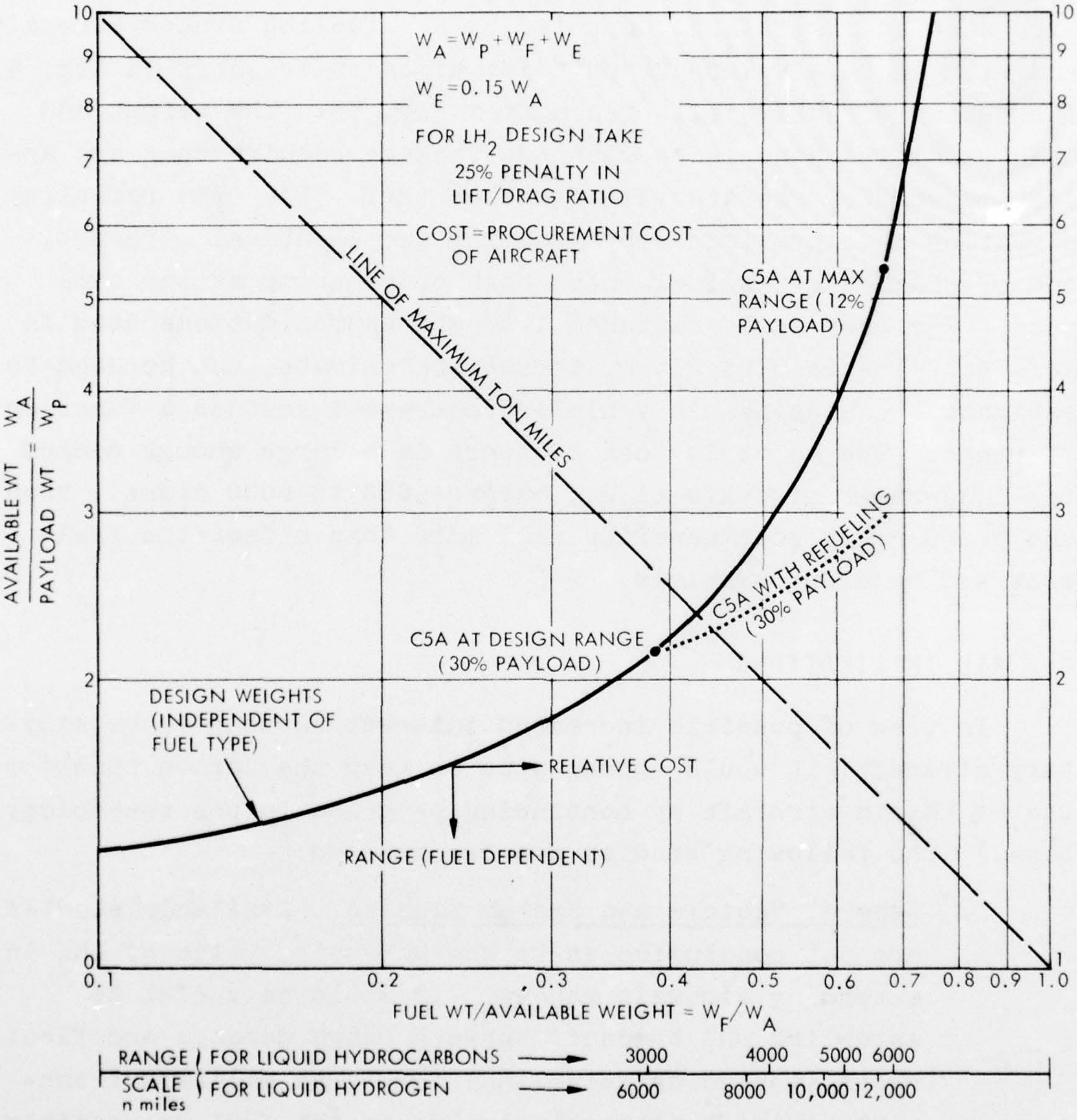

FIGURE 5. Comparison of the Cost of Range in Aircraft, With the Gross Weight of a C5A, Fueled With Either Liquid Hydrocarbons or Liquid Hydrogen

military to provide their own source of supply of LH_2--even at each base. If technology could provide relatively small independent supply units, this prospect could become viable.

D. NUCLEAR PROPULSION FOR MILITARY VEHICLES

In looking to the long-range future, it is necessary also to assess the prospects for extended use of nuclear propulsion systems in the military. Since the specific fuel consumption of a nuclear power source is essentially zero, nuclear propulsion, in principle, offers unlimited range to vehicles that can accommodate it. There are two major problems in this accommodation. The first relates to safety both in normal operation and in destructive situations. This problem is much more easily handled in ship and submarine applications than for aircraft or land vehicles. The second problem relates to the physical size of nuclear systems. Currently, only fleet submarines and large naval combatant vessels, such as carriers, can easily provide for the size and weight requirements of nuclear propulsion systems.

In looking to the future, it is not apparent how the safety problems associated with the use of nuclear systems on aircraft or land vehicles may be solved. It appears that such applications are at best far in the future. With regard to naval applications, however, these safety problems have not been prohibitive and it would seem advantageous to extend the use of nuclear systems if cost and size problems can be met. It is of interest to examine this question here relative to the state of technology.

Figure 6 shows the specific power requirements of different classes of Navy ships. The size and speed of the ship determine its specific power (hp/ton) needs. Since a limited percentage of the total vehicle can be devoted to power plant, the specific

power needs of the vehicle translate into a restriction on the specific weight of the propulsion system. The relationship is

$$\text{Vehicle specific power} \sim \frac{\text{Power plant weight fraction}}{\text{Power plant specific weight}} \; .$$

The approximate lower limit on the specific weight of current nuclear systems is indicated on the figure. It is apparent from this view that a reasonable goal for technology base would be to reduce the specific weight of nuclear systems so that they could be effectively used for small naval ships. There is already considerable technology base work sponsored by the Navy addressed to this problem and it is recommended that these programs be continued and expanded where they appear to be attaining their goal.

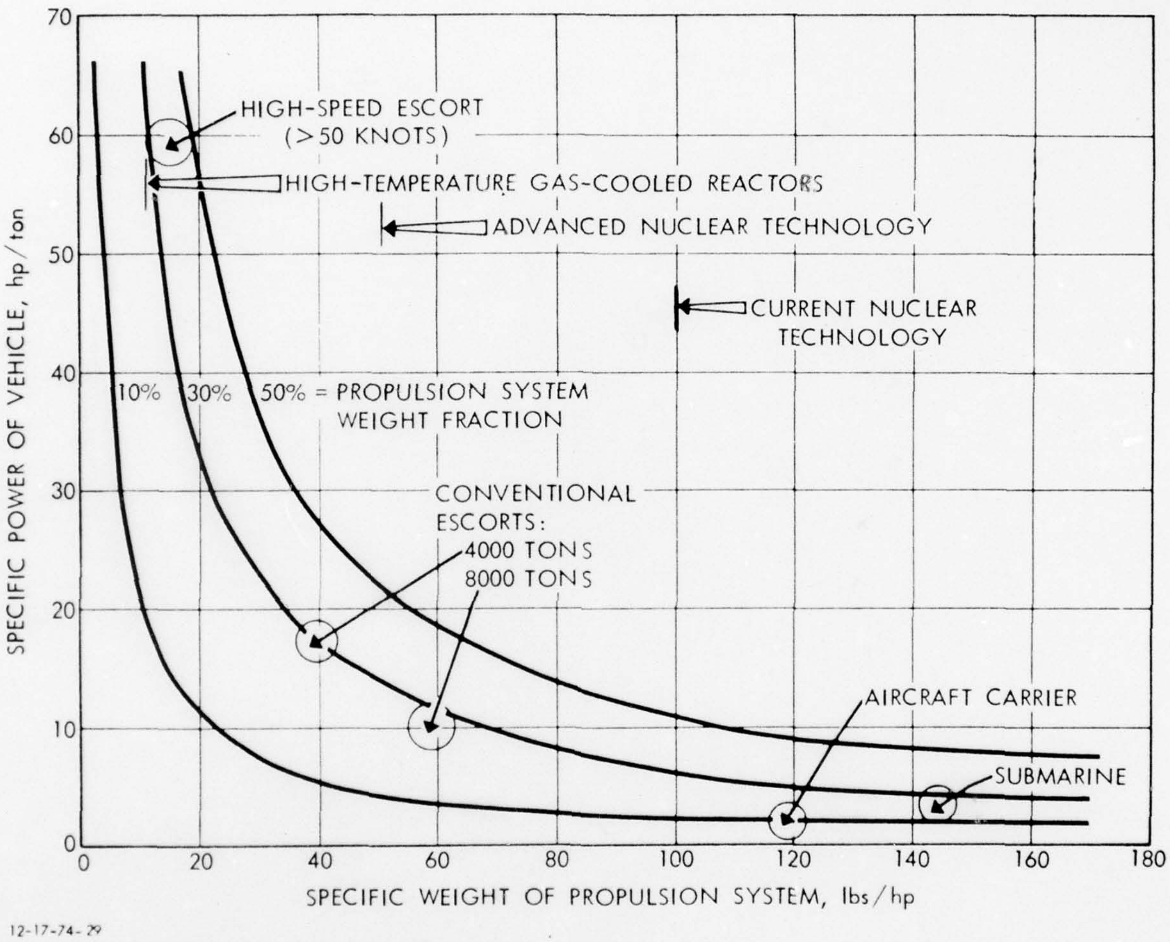

FIGURE 6. Nuclear Propulsion Prospects (Ref. 13)

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DOD ENERGY R AND D. PART II. MILITARY FUEL OPTIONS. PERFORMANCE--ETC(U)
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APPENDIX A

TASK ORDER

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
1400 WILSON BOULEVARD
ARLINGTON, VIRGINIA 22209

TASK ORDER FOR WORK TO BE PERFORMED
BY
INSTITUTE FOR DEFENSE ANALYSES

TASK ORDER T-116 DATE: 21 January 1975

You are hereby requested to undertake the following task:

1. TITLE: R&D on Energy Management

2. TECHNICAL SCOPE: The purpose of this task is to review DoD energy uses and develop guidelines for Technology Base R&D on Energy Management. The task will be in three parts. The first part will be to review the studies that have been made of the overall DoD energy use and/or relieving dependence on critical sources of energy. These will be related to the National Energy R&D program to determine where DoD should rely on civilian R&D and where it should have its own programs.

The second part of the task will be to survey the possible impact on the DoD energy management problem of R&D programs related to fuel options. This will include multifuel capability in liquid hydrocarbons and possible future alternate fuels, specifically liquid hydrogen and nuclear sources.

The third part of the task will examine DoD energy-use at fixed bases and in industrial processes where DoD is a large consumer but must rely on civilian R&D for improvements. An investigation will be made of possibilities that exist for DoD to cooperate with civilian agencies to further R&D in these fields.

3. SCHEDULE: Work will commence on November 1, 1974 and be completed by October 31, 1975.

4. ODDR&E COGNIZANCES:

(a) Overall cognizance of this task is within the Office of the Deputy Director (Research and Advanced Technology), ODDR&E.

(b) Subtask assignments will come under the cognizance of the Assistant Director (Engineering Technology).

5. SCALE OF EFFORT: Two man-years at the average rate of two man-months per month.

6. REPORT DISTRIBUTION AND CONTROL: All report distribution will be controlled by the office of technical cognizance.

7. SPECIFIC INSTRUCTIONS AND LIMITATIONS: None. Changes in scale of effort will not be made without the consent of DARPA. A "need-to-know" is hereby established in connection with this Task and access to information in the field of this Task is authorized for participating personnel and each supervisory and advisory personnel as deemed necessary. Department of Defense support, such as access to classified documents and publications, security clearances, and the like, necessary to complete this Task, will be obtained through the Director, ARPA.

for George H. Heilmeier
Acting Director

ACCEPTED: Alexander H. Flax
Alexander H. Flax
President, IDA

DATE: January 10, 1975